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An integrated approach to the analysis of eighteenth-century horns

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Declaration

I declare that this thesis was composed by me and that the work described within is my own, except where stated otherwise in the text.

Lisa Norman

March 2013

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Abstract

The revival of interest in historical performance practice has led to much speculation concerning how early instruments might have been made, played and in particular how early ensembles might have sounded. At the beginning of the eighteenth century, the hunting horn became increasingly accepted as an integral member of the orchestra. This new role led to changes in the design of the instrument and also in player technique which in turn led to a change in the sound quality or timbre of the instrument.

There are many surviving examples of eighteenth-century horns in museums and private collections worldwide and the significant variation amongst these instruments is evidence of this new and innovative era in the development of the horn. Perhaps the most significant and contentious debate in the discussion on horn technique from this period concerns how and in what situation the hand should be employed within the bell of the instrument. This is the central issue on which the following research has been based.

A multifaceted approach was adopted in order to gain a broader insight into the mysteries surrounding the eighteenth-century horn. The various methods used include: acoustical analysis of the effect of the hand in the bell of the horn on intonation and ease of playing in the high register, and analysis of variation in tonal characteristics; ergonomic analysis which lends a practical perspective to the issues surrounding playing technique; bore profile analysis in order to efficiently and effectively compare a large amount of data concerning this fundamental aspect of horn design.

The results have shown that an integrated approach to the analysis of eighteenth-century horns, performed systematically on measurements from a large database of over one hundred instruments, has the potential to provide an insight into the development of the horn from a number of different perspectives. A large scale analysis such as this allows trends to be observed which shed new light on regional variation in horn design and playing technique over time.

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Glossary

bore profile The shape of the internal dimensions of a brass instrument, not including information about bends in the tubing or the **wrap**.

corpus The main body of coiled tubing on a horn, into which **crooks** and **couplers** can be inserted.

coupler A length of tubing, used in combination with a **terminal crook** and sometimes other **couplers**, which the **natural horn** player uses in order to put the instrument into different keys. They are near cylindrical in shape allowing additional **crooks** or **couplers** to be inserted at either end.

crook A length of tubing which the **natural horn** player uses in order to put the instrument into different keys. The earliest known reference to horn crooks comes from 1703, in a bill by Leichamschneider.

cup The cavity in the **mouthpiece** over which the player places their lips. The narrowest part of the internal bore of the mouthpiece is often called the throat and the section immediately following this which is inserted into the instrument, the backbore.

double horn A type of horn commonly used by modern horn players which combines two lengths of instrument: a 12-ft length of tubing in F, historically a common key for the horn to play in, and the shorter 9-ft length of tubing in $B^{\flat}$, providing the player with more security in the high register. A thumb valve allows the player to move easily between these two lengths. Descant and triple horns are becoming increasingly popular, and include an even shorter length of tubing, further increasing the security in the high register.

ferrule A metal fitting which covers the join between two sections of tubing on a brass instrument, often shaped like a ring or cylinder.

french horn A more historic term, still sometimes used today (mainly by non-horn players), to describe what is commonly referred to as simply the 'horn'.

garland A flat strip of metal which encircles the very last part of the bell flare on a brass instrument, providing extra reinforcement in this more fragile area and also commonly a place for instrument makers to inscribe their mark.

hand-stopping A technique particular to horn playing where the hand is fully closed over the bell. Composers today often ask for players to hand-stop when they require a brassy, nasal tone quality. In the nineteenth century, the range of hand positions varied from fully stopped to fully open with many degrees of closure in between. A more common term for this historic method of playing with the hand in the bell is 'hand technique', however the two terms are sometimes used interchangeably.

harmonic series A set of pitches whose frequencies are all integral multiples of one fundamental frequency. This term is often mistakenly used to refer to the **natural modes of resonance** of a brass instrument, a set of pitches which do *not* conform to the harmonic series, but are a close approximation.

harmonics These are the component frequencies which make up a **harmonic series** and are integer multiples of the fundamental frequency of a particular series.

inventionshorn A type of **natural horn** invented in the mid-eighteenth century, identifiable by its fixed **mouthpipe**, and by **crooks** which fit into the middle of the horn **corpus**. It is likely that the first inventionshorn crooks fitted into two sockets on the body of the horn, much like **terminal crooks** do, but surviving examples demonstrate a sliding crook which could also be used to alter the tuning of the instrument.

lipping A term commonly used by brass players to describe the process of manipulating the pitch of a note using a combination of breath control and

embouchure control (often involving changes to the oral cavity). Early horn and trumpet players would have been required to use this technique in order to bring wayward **resonances**, such as the eleventh and thirteenth, in to tune. This skill is not so necessary on the modern horn as valve combinations and hand technique can be used to overcome intonation difficulties.

mandrel A type of mould shaped to the exact dimensions of an internal section of a brass instrument, used by makers to shape the metal when producing sections of tubing such as the bell flare or the **mouthpipe**.

master crook The name for a type of **terminal crook** which was used in conjunction with **couplers**.

mouthpiece The part of a brass instrument on which the lips of the player are placed, and in the case of the orchestral horn (and most other brass instruments), a detachable section which can be easily transferred between instruments, musicians often having a preferred mouthpiece on which they predominantly play.

mouthpipe A short section of tapered tubing into which the **mouthpiece** is inserted.

natural horn The term used to describe a horn without valves on which only the **natural resonances** of the instrument can be sounded, prior to any pitch manipulation with either the embouchure or the hand. Similarly, a trumpet without valves is referred to as a natural trumpet.

natural modes of resonance When used in the context of the notes obtainable on a natural brass instrument, these are the frequencies at which standing waves readily occur in the air column of the instrument when excited by the lips of the player.

rim When used to describe part of a **mouthpiece**, it refers to the surface on which the lips of the player are placed. When used to describe part of the bell, it refers to the circular edge at the very end of the bell flare.

stay A metal component which provides additional support between potentially weak sections of tubing on a brass instrument, such as the **mouthpipe** or the bell.

terminal crook A type of crook with a tapered **mouthpipe** into which a **mouthpiece** can be inserted, distinct from a **coupler** which does not receive the mouthpiece. A **master crook** is of this type.

wrap The way in which the tubing is laid out on a brass instrument, often helping to distinguish between different models.

Abbreviations

The abbreviations for the musical instrument collections listed below have been compiled for the new edition of the New Grove Dictionary which is in preparation.

a *ante* [before]

c *circa* [about]

c. century

fl *floruit* [was active as a maker]

p *post* [after]

A.G.lj Universalmuseum Joanneum, Graz, Austria

A.KR.sk Musikinstrumentenmuseums Schloss Kremsegg, Kremsmünster, Austria

A.W.km Kunsthistorisches Museum (Sammlung alter Musikinstrumente), Vienna, Austria

B.B.mim Musée des Instruments de Musique, Brussels, Belgium

CH.B.hm Musikmuseum, Historisches Museum Basel

CZ.P.nm National Museum (including Museum of Czech Music) [Narodni Muzeum v Praze, Muzeum Czeské Hudby], Prague, Czech Republic

D.B.im Musikinstrumenten Museum, Staatliches Institut für Musikforschung, Berlin, Germany

D.EU.s Schloss Eutin, Eutin, Germany

D.LE.u Musikinstrumenten-Museum der Universität Leipzig (Grassi Museum), Leipzig, Germany

D.LÜ.mk Museum für Kunst und Kulturgeschichte der Hansestadt Lübeck, St. Annen Museum, Lübeck, Germany

D.M.dm Deutsches Museum, Munich, Germany

D.M.sm Stadtmuseum, Munich, Germany

D.N.gnm Germanisches Nationalmuseum, Nuremberg, Germany

E.B.mi Museu de la Música, Barcelona, Spain

F.P.cm Cité de la Musique, Musée de la Musique, Paris, France

GB.CAS.prowse Martin Prowse, private collection, Castle Douglas, United Kingdom

GB.E.chick John Chick, private collection, Edinburgh, United Kingdom

GB.E.u Edinburgh University Collection of Historic Musical Instruments, Edinburgh, United Kingdom

GB.L.hm Horniman Museum, London, United Kingdom

GB.NW.cm Norfolk County Council Museums Service (St Peter Hungate Church Museum and Strangers Hall Museum), Norwich, United Kingdom

GB.O.ub Bate Collection, University of Oxford, Oxford, United Kingdom

NL.DH.schepel Louise Schepel, private collection, The Hague, Netherlands

US.B.mfa Museum of Fine Arts, Boston, MA, U.S.A.

US.NY.mma Metropolitan Museum of Art, New York, NY, U.S.A.

US.W.si Smithsonian Institution (National Museum of American History), Washington, D.C., U.S.A.

Chapter 1

Introduction

1.1 Aim

Brass musical instrument manufacture enjoyed something of a golden era in the eighteenth century; there were numerous prestigious instrument makers, and design and manufacturing techniques progressed rapidly. However, examples of brass instruments surviving from the eighteenth century are relatively scarce, and many have no marks to identify the maker, date, or place of manufacture. In addition, information regarding playing technique and instrument manufacture is not well documented. This leaves musicians, instrument makers, historians, and museum curators with considerable uncertainty regarding the selection of instruments appropriate for the repertoire; the provenance of individual surviving instruments in particular, and the techniques employed to make and play these instruments in general.

The overarching aim of this thesis is the use of novel, multi-disciplinary, analytical techniques to map the evolution of the horn and horn playing in the eighteenth century, and to provide a systematic approach to instrument analysis based on features of the bore profile, the 'wrap' and the acoustical response. A database of detailed photographs and measurements taken from horns in museums and private collections throughout Europe and North America forms the basis for this

analysis. Aspects such as regional variation in horn design and player technique are explored, and the implication this has on the tone quality of the instruments is discussed.

1.2 Context

Of all the orchestral instruments, the horn has perhaps the greatest uncertainty surrounding its evolutionary history as a result of one significant aspect of performance technique: the use of the hand in the bell. It is generally acknowledged that at some point in the eighteenth century it became accepted practice for players to manipulate the pitch of certain notes by partially covering the bell of the horn with the hand. This technique enabled players to correct the intonation of otherwise out of tune notes, and it also increased the range of pitches available to the player who had previously been confined to only the open natural notes (resonances) of the instrument. Another significant feature of employing the hand within the bell of the horn is to make extremely high notes more secure than they would otherwise be [Benade, 1990; Merewether, 1978].

The chronological and geographical adoption of this practice is a subject of highly contentious debate amongst historians and practitioners of historically informed performance. An alternative approach is proposed, building on the research already carried out, in order to bring a new angle to the discussion.

One of the most significant recent publications concerning early horn history, is a collection of articles in the book, *Jagd- und Waldhörner: Geschichte und musikalische Nutzung* [Schmuhl & Lustig, 2006]. The authors adopt various approaches in attempting to fathom the mysteries surrounding the early horn. These include explorations into social and political histories, iconographical evidence, contemporary manuscripts, and documents on technique.

Of particular interest in this publication: Myers [2006] presents bore profile measurements from a range of orchestral and hunting horns, and analyses the taxonomic and acoustical properties of these instruments, focusing on the differences

between a sample of four *trompes de chasse* (French hunting horns). Myers has also carried out extensive research on the taxonomy of brass instruments for his Ph.D thesis, employing similar interdisciplinary methods [Myers, 1998]. The following work draws on and extends techniques used by Myers, embracing both musical instrument acoustics and historical investigation in order to provide new insights into the organology of early brass instruments. Previously unexplored territories include ergonomic analysis and systematic bore profile matching of eighteenth-century horns.

Figure 1.1: Photograph of a crooked horn by the instrument maker Angoulvant (NL.DH.schepel, 1).

Research into this era of horn playing and design not only contributes to our general understanding of the instrument's history, but may significantly influence the performance practice decisions made by 'period' ensembles. The research is also of direct benefit to instrument makers, museum curators and historians, offering new insights into the dating, identification and construction of anonymous instruments.

1.3 Scope

The core of this thesis is a systematic analysis of detailed measurements from over one hundred eighteenth-century horns from twenty-five different museums and collections worldwide. One of the first important decision to be made concerning the purpose of the survey, was precisely what information to record about each horn examined.

From an acoustical perspective, the bore profile is fundamental to how a brass instrument sounds, and so detailed measurements of each entire horn were recorded as a key priority. This information can also be used in computational models to predict what damaged or fragile instruments might have sounded like. From an ergonomic point of view, the key dimensions of the layout of the horn were noted, and a good quality photograph was taken at a distance in order to minimise perspective distortion.

This was the basic data recorded during each horn examination but as the research progressed, additional data was increasingly gathered, such as acoustic input impedance measurements, the weight of the instrument, and photographs of exact manufacturing details (seams, garlands, stays, ferrules, etc.). The gathering of all of this information has been an ongoing process throughout the period of the last four years and will continue to grow as more horns are added to the database in the future.

'Eighteenth-century', is the time-span indicated by the title of this thesis, but this is an approximation, with some leeway occurring on either side of the century; indeed, it is during the eighteenth century that many exciting changes occurred in the history of the horn, but the late seventeenth and early nineteenth centuries have offered up some fascinating instruments which were too important not to be included in this discussion. Occasionally the data analysed in the following chapters has also incorporated modern instruments and modern copies of early instruments, purely for the sake of comparison and to place the discussion in a wider context.

It should also be noted that the development of the horn diverged in the eighteenth

century and two separate paths were forged; that of the hunting horn and of the orchestral horn. The two different paths resulted in the emergence of separate and distinct instrument design and similarly playing technique, a distinction which remained throughout the rest of the horn's history. Instruments included in this survey are predominantly those used in an orchestral setting (an example is shown in the photograph in Figure 1.1), but a number of hunting horns (example photograph in Figure 1.2) have also been examined. What distinguished a hunting horn from an orchestral horn would initially have been the context in which each was played, but as their separate functions became established, the orchestral horn developed into a more compact instrument, which early on was adapted to receive interchangeable lengths of tubing known as crooks. Further discussion on the difference between these two types of horn can be found in Chapter 5.

Figure 1.2: Photograph of wide-coiled hunting horn by Hieronymus Franck, dated 1716 (D.N.gnm, W 3013).

There are also instruments which can not easily be categorised; some of the most interesting examples have questions marks over their intended purpose, or perhaps they had several purposes. A full and detailed listing of all of the horns from this survey can be found in Appendix A.

1.4 Structure

Chapter 2 serves not only as a review of past and present literature, but also as the historical backdrop for the various novel approaches to early brass instrument research discussed in the subsequent chapters. Considered in isolation, the acoustical measurement and ergonomic analysis of historic horns would have limited value, but when combined with the archival knowledge already gathered, it can provide a refreshing new insight into this field of study. The first part of the review evaluates the key sources encountered in this research, whilst the second part highlights the importance of the historic object, itself a key source with the potential to provide untapped information when subjected to scientific analysis in a systematic manner and on a large scale.

Chapter 3 deals directly with the **sound** of the horn and explores some of the influencing factors of its acoustics. This is an important discussion because it is the tone of the early horn which is of particular relevance to musicians and instrument makers. It is in this chapter that the significance of the bore profile, a recurring theme throughout this thesis, is first introduced. The importance of the shape of the instrument's air column in determining its acoustics is discussed and the basic theory explaining why the timbre of a brass instrument becomes bright and 'brassy' with increasing dynamic level is explained. The rest of the chapter is devoted to analysing the results from a set of non-invasive acoustical experiments designed to explore the brassy characteristics of historic horns. Discussion includes how the results relate to instrument design.

Player **technique** also has a significant impact on what early horns might have sounded like, and so Chapter 4 tackles this controversial issue from an acoustic standpoint. The reasons for the change in technique during this experimental

period in the history of the horn are briefly described and the main method of analysis based on the measurement of acoustic impedance is explained. Following this, the chapter is split into two parts reflecting the two main techniques which were present amongst eighteenth-century brass players at this time; the first part looks at the effect of embouchure manipulation ('lipping') in order to alter the pitch of notes, and the second part concentrates on the technique of employing the hand within the bell of the horn for the same effect.

The **design and ergonomics** of early horns is the subject of Chapter 5 and like the previous chapter, the aim of this one is also to explore what information early horns can provide about how they might have been played. Analysis techniques using scaled outlines and photographs to examine the wrap of the horn and related key dimensions are reviewed. Following on from this, a more practical approach to the issue of hand technique is discussed, involving the adaptation of an ergonomic diagram in order to compare and present the horn data more clearly.

Chapter 6, the final results chapter, draws on many of the aspects of the previous four chapters, but with a particular focus on comparing the **bore profiles** of early horns and how this relates to instrument making and manufacture. The method of taking detailed measurements of a horn is described here in detail, along with an explanation of the software tool used to compare the large database of bore profile measurements. The rest of the chapter is devoted to interesting examples of horn manufacture and design which were brought to light as a result of the bore profile matching analysis tool.

Finally, Chapter 7 brings together the many different strands of this body of research in order to show the value of an interdisciplinary approach to early horn history such as this.

Appendix A lists the main details for all horns included in this study and also has references with links to which instruments are specifically discussed in which chapters. Appendix B describes the content of text files which make up the database of bore profile measurements, and includes a CD of data files used by the bore profile comparison software. Appendix C provides additional data from the playing experiments looking at the technique of lipping on different horns and mouthpieces.

Appendix D shows the analysis carried out in order to determine the level of potential error due to distortion when taking photographs. Appendix E includes two articles which use similar techniques to those described in this thesis, but covering slightly different subject matter.

Chapter 2

Various approaches to early horn research

This chapter reviews the existing literature relating to the horn in the eighteenth century. Section 2.1 explains the different sources from which relevant information can be extracted. Next, Section 2.2 looks at the prevailing interpretations of primary sources in the field of organology, with a particular focus on the discussion of playing technique. Then less common approaches to historical instrument research are explored in Section 2.3. Finally, the current state of eighteenth-century horn research is summarised in Section 2.4.

2.1 Various sources

There are limited sources available to the researcher wishing to discover more about the horn in the eighteenth century. These will be discussed in detail in the following subsections, but a brief overview is presented first.

One of the most common approaches adopted is to examine the methods and tutors which were written at the time (2.2.1), particularly when searching for information about performance technique. Information from these sources is less likely to

be ambiguous since they were published for the main purpose of instructing and informing. Unfortunately very few treatises have survived and in those that have, the information is surprisingly limited concerning playing technique.

Other sources frequently examined include concert programmes, published anecdotes, receipts, inventories and other such archival evidence (2.2.1), but again theses are scarce and contain limited information. Some researchers have looked at iconography surrounding the horn (2.2.2), which provides an interesting angle from the perspective of the painter or artist. Another useful approach has been to analyse manuscripts and musical scores (2.2.3), the very dots and dashes which would have confronted horn players of the day.

Despite the variety of sources to draw on, evidence is scarce surrounding the question of where and when hand horn technique was first adopted in the eighteenth century, and the ambiguity surrounding this area of horn history frequently engenders great debate amongst musicians and scholars alike.

However, there is still room for discovery as not all sources or methods of research have been fully exhausted: the study of musical instrument acoustics (2.3.1) is not a new discipline, yet it has had limited application to historical instrument research so far; ergonomics on the other hand (2.3.2) is a relatively new research area with a largely untapped potential for providing new insight into the way historic musical instruments might have been played; whilst there has certainly been some discussion about the design and manufacturing processes of eighteenth-century brass instruments (2.3.3), a broad and systematic analysis of surviving horns is missing from this area of research.

2.2 Standard approaches

Walter F. H. Blandford was one of the first scholars to take a keen academic interest in the history of the horn. His varied interests as horn player, collector and musicologist meant that his approach to researching the horn was also varied. In Blandford's [1922] article, 'Studies on the Horn, No. I: The French Horn in England', he

draws on an impressively wide range of sources to illustrate the horn's history. He even discusses hand technique in the context of ergonomic convenience, although briefly [Blandford, 1922, p.546]. The assurance with which he writes about the progression of hand technique in Europe based on evidence from only a few isolated sources [Blandford, 1922, p.546] might seem slightly presumptuous today in light of new evidence from works written for horn players at the court of Dresden. Nevertheless this is a valuable short overview of the horn in eighteenth-century England, written at a time when organological research was starting to become more widespread.

By the mid-twentieth century there was increasing interest in research into the historical development of wind instruments with many specialist books appearing on the subject. In 1947, the first comprehensive book on the history of the horn was published: *The French Horn* by Birchard Coar, with chapters on subjects including early horn and trumpet comparison, the invention of the tuning slide and crooks, and also more controversial issues such as, 'Hampel's discoveries'. At several points, Coar includes footnotes indicating that the point being raised is controversial and there follows a short but interesting discussion on the validity of the relevant sources [Coar, 1947].

Blandford had been approached to write a book on the horn around this time (middle of the twentieth century), but having turned down the offer, his friend and fellow horn player, Reginald F. Morley-Pegge stepped in to take up the cause. Morley-Pegge's [1960] book with the apparently popular title, *The French Horn*, contains many important insights into the historic instrument. He draws heavily on methods and tutors for his discussion of player technique and devotes a whole chapter to this issue [Morley-Pegge, 1960, pp.70-120]. Morely-Pegge is one of the first authors to question the importance of the evidence surrounding the frequently cited 'invention' of hand-stopping by horn player Anton Joseph Hampel in the mid-eighteenth century, giving recognition instead to the likelihood that Hampel's role was perhaps more of establishing and codifying the technique [Morley-Pegge, 1960, p.87].

Another seminal work is the book by Horace Fitzpatrick, published ten years later in 1970, called *The Horn and Horn-Playing: and the Austro-Bohemian tradition*

from 1680 to 1830 [Fitzpatrick, 1970]. As the title suggests it is a more concentrated look at one geographical region and era of horn playing, but the research Fitzpatrick has carried out is extensive. Particularly useful is the detailed information on the design and dimensions of numerous early horns, illustrated with good quality photographs. Fitzpatrick makes some controversial remarks which have helped spark discussion and debate in early horn circles since, such as the extent to which horn and trumpet were doubled in the early orchestral years [Fitzpatrick, 1970, pp.66-67]. On the question of hand technique, he agrees with Morley-Pegge and goes so far as to suggest that the beginnings of the technique may have been implied in Fantini's trumpet method of 1636 [Fitzpatrick, 1970, p.83].

John Humphries published a concise and informative book about the early horn in 2000: *The Early Horn: A Practical Guide* [Humphries, 2000]. A large section of the book looks at the music written for the early horn and uses this as the starting point for a discussion on technique and interpretation. The intended audience for the book therefore, is primarily the musician rather than the scholar, but it also covers the historical aspect of the instrument. In the chapter dedicated to technique, Humphries mentions not only hand technique, but also the method of 'lipping' notes in to tune [Humphries, 2000, p.55]; this is a way of altering the pitch of notes using the embouchure, which has only been discussed in the context of early horn technique in more recent literature (the use and meaning of the word 'lipping' is discussed in more detail in Section 4.1 and also appears in the glossary at the beginning of this thesis). Humphries is very thorough in providing a broad view of the early horn in a number of different geographical regions throughout Europe, helping to emphasise regional variation in playing technique.

Thomas Hiebert has carried out some fascinating research focussing largely on the analysis of eighteenth-century manuscripts. His article, 'Virtuosity, experimentation, and innovation in horn writing from early eighteenth-century Dresden' published in the *Historic Brass Society Journal*, suggests that some form of hand technique might have been employed by at least the second decade of the eighteenth century amongst the skilful players at the court of Dresden [Hiebert, 1992]. He is one of the first scholars to propose a more precise date for the introduction of hand technique, alternative to the controversial 'Hampel discovery' date (the following

section, 2.2.1, provides more information about the origins of this controversy). Hiebert's theory is backed up with discussion and illustrations using many musical examples.

A related article by Hiebert has appeared more recently in the formative book *Jagd- und Waldhörner: Geschichte und musikalische Nutzung* in which he casts his critical eye over English manuscripts: 'Extraordinary horn writing in *The Egerton Manuscript Collection*: A contribution to the history in mid-eighteenth century England' [Hiebert, 2006]. The discovery of passages of chromatic writing in music from this period has lead Hiebert to suggest an earlier use of hand horn technique in England than previously thought [Hiebert, 2006, p.246].

Whilst current opinion amongst scholars and musicians tends to favour that of Hiebert, concerning the advent of hand technique, an interesting article in *The Horn Call* by Drew Stephen [2007] puts forward a case that there may have been much more extensive use of the lipping technique until late in the eighteenth century. This discussion in his article, 'To Stop or Not to Stop', underlines the fact that player technique is an area of early horn history which is still very much open for debate.

2.2.1 Written accounts

Written sources can include teaching material such as methods, tutors, treatises, and miscellaneous items such as inventories, programme notes and accounts. These are the types of archival document most commonly referred to by the horn historians discussed in Section 2.2 previously.

There were great changes taking place concerning the development of the horn in the eighteenth century, particularly surrounding the area of playing technique and yet, written descriptions of what to do with the hand in the bell seem conspicuously lacking; in the methods and tutors of the day, there are musical exercises clearly involving many non-series tones where such a discussion on hand technique, or other means of getting the notes, would seem pertinent.

Hampel is the name of the famous Bohemian horn player most frequently referred to as either 'inventor' or 'codifier' of hand technique, however opinion is divided as to the significance of his role in this. Those who place great importance on Hampel's role often cite a passage in Heinrich Domnich's [1807] *Méthode de Premier et de Second Cor* as evidence. The text refers to Hampel:

> Ce fut pour lui un trait de lumière, et son génie étendant rapidement une découverte due au hazard, il vit le moyen, en présentant et retirant alternativement son tampon, de parcourir sans interruption l'échelle diatonique et chromatique de toutes les gammes. [Domnich, 1807, p.iv]
>
> [In a flash of inspiration due to this chance discovery, he realised that by alternately inserting and withdrawing the mute, he could cover the complete range of diatonic and chromatic scales without a break.] (translation by author)

Whilst this might seem like definitive evidence, the case becomes slightly more clouded when considering the two playing methods Hampel himself wrote: *Lection pro Cornui*, *c*.1762, [Hampel, c1762]* and the *Seule et vraie méthode*, thought to have been written *c*.1750 but not published till *c*.1798 [Hampel & Punto, c1798]. Neither of these tutors make any mention of his 'newly discovered' technique, despite many of the included exercises and duets requiring some method of pitch manipulation for the non-series notes [Morley-Pegge, 1960, p.91].

Hampel had a famous pupil, the internationally renowned horn virtuoso known as Giovanni Punto (born Jan Václav Stich) who was a strong supporter of the new hand technique. As well as being a contributor to the publication discussed above by Hampel, the *Seule et vraie méthode*, Punto also wrote a lesser known work around the same time, his *Etude ou Exercice Journalier*, *c*.1796 which is similarly, curiously silent on the subject of hand technique [Punto, c1796].

It was in fact a clarinet player and composer, Valentin Roeser, who appears to have broken the silence surrounding the mystery of horn technique in his *Essai d'instruction*, published in 1764 [Roeser, 1764], around the same time as Hampel's works were being written and published. Roeser's orchestration guide makes a clear reference to the use of the hand in the bell:

*Unfortunately the manuscript was lost in the Second World War but a selection of exercises from the method are reproduced in [Morley-Pegge, 1960].

> Les tons que j'ai marqué de cette Croix sont trop haute, mais on les peut faire justes en mettant la main dans le pavillion du Cor, surtout quand il y a des notes blanches ou noires. [Roeser, 1764, p.14]
>
> [The notes which I have marked with a cross are too sharp, but they can be played by placing the hand within the bell of the horn, especially when the notes are minims or crochets.] (translation by author)

Not only does Roeser refer to hand technique as a means of correcting intonation, but later on in the text he also mentions that a number of notes outside of the natural series can be played in this manner [Roeser, 1764, pp.14-15]. This is the only detailed description of hand technique to have survived from the eighteenth century and as such it is an extremely valuable source for researchers. It is tempting to draw conclusions from this text about the date of origin of hand technique but as the following interpretations show, primary sources such as this are subjective by nature.

Richard Seraphinoff suggests that the matter-of-fact style in which the explanation by Roeser is written implies that the use of the hand in the bell must have been a 'standard part of the horn player's technique', and therefore had most likely been widely used for a number of decades prior to the article's publication [Seraphinoff, 1996]. Stephen on the other hand thinks that Roeser's 'cautious approach to hand-stopping' implies that hand technique was still in its early stages of development [Stephen, 2007]. Morley-Pegge makes the interesting point that Roeser was a clarinet player, not a horn player, and as such he might have been more inclined to divulge the details of hand technique then Hampel or Punto if some vestige of the secrecy surrounding guilds remained at this time [Morley-Pegge, 1960, p.89]. It is also worth noting that Roeser felt comfortable enough writing about the playing technique of the horn to include it in his general advice for composers, which would suggest that it was already well established by this date.

Of the small handful of horn methods and tutors from the eighteenth century, the majority were published in England, although the content of these are all extremely similar. *The compleat tutor for the french horn* is attributed to Christopher Winch, and its publication date of 1746 makes it one of the earliest known documents devoted entirely to the horn [Winch, 1746]. Subsequent publications based on

this title include: *The french horn master* [Winch, c1750] and *Instructions for the french horn* [anon., 1757].

The last reincarnation of this method was published *c*1780: *New instructions for the french horn* [anon., c1780]. It has large parts of text quoted directly from Winch's tutor of thirty years previous, suggesting that perhaps it was not the most up to date method of the day, although one area which has been expanded in the more recent method is the section on technique:

> [...] should you want to make the chromatic tones, you may hold the horn with your right or left hand as near as you can to the mouthpiece, the bell to bear against your side, one hand must be within the edge of the bell ready to put into the pavillion or bell of the horn as notes may require. [anon., c1780]

This description is quite vague, perhaps because it is difficult to put into words what the technique involves, or perhaps also because the specifics of the technique varied from player to player.

Indeed, three distinct methods of employing the hand within the bell are described in Othon-Joseph Vandenbroek's undated and unpublished manuscript from the late eighteenth century. The first is difficult to imagine as no figure or diagram is included:

> Some professors, when playing open notes keep the thumb down, bringing it into its natural position, which completely closes the bell, for stopped notes. This method is not one of the best. ([Vandenbroek, c.1800] approximate translation taken from [Morley-Pegge, 1960, p.95]*)

Vandenbroek was able to speak with some authority on the subject since his profession was as a horn player in the Paris Opéra orchestra. The second method he mentions is similar to the description in *New instructions for the french horn* (previous quote), where the hand is brought in and out of the bell as needed. It is the third method however, which Vandenbroek favours; he advocates a more closed general hand position, allowing the hand to be readily available for covering over the bell when necessary [Vandenbroek, c.1800]. That these three distinct styles of

*The original text in French has not been quoted here because the hand writing is illegible in places and the spelling is mostly phonetic. A facsimile of the manuscript can be found in [Saint-Arroman, 2003].

hand technique had emerged by the end of the eighteenth century would suggest that the use of the hand in the bell had been ongoing for some time.

Methods and tutors are not the only sources where reference to playing technique in the eighteenth century can be found. There seems to have been a mixed response to the tonal qualities of hand technique in the English concert scene as documented by Charles Burney in *The cyclopaedia* under the entry for 'Horn' [Rees, 1819]. In the following quotation, he is talking about the hand technique of the renowned virtuoso Punto, who gave concerts during his visits to London in the early 1770s:

> We have often thought that Ponto [*sic*], with all his dexterity, produced some of these new notes with similar difficulty, to a person ridden by the *night mare*, who tries to cry out, but cannot. [Rees, 1819]

What is most interesting in this passage, is Burney's use of the word 'new' to describe the hand-stopped notes, suggesting that in England anyway, hand technique was a relatively new phenomenon.

Evidence to support this theory can also be found in the description of a London concert from 1773, this time featuring the equally famous horn player, Willem Spandau. Unlike Burney, the commentator John Hawkins was impressed by the tonal quality of the technique, particularly since Spandau was playing a piece in the key of C minor requiring the difficult interval of a minor third:*

> The French horn [defects] of late have been so palliated, as to require no particular selection of keys [...] all the intervals seemed to be as perfect as in any wind-instrument; this improvement was effected by putting his right hand into the bottom or bell of the instrument, and attempering the sounds by the application of his fingers to different parts of the tube. [Hawkins, 1776, p.144]

Hawkins' inclusion of a description of the technique, using the words, 'of late', strengthens the suggestion that hand technique was still in its infancy in England at this time. There is also the possibility that Hawkins was impressed with the hand technique of Spandau in particular, on this notoriously difficult instrument.

*The notes of a minor key deviate more from the natural resonances of a brass instrument than those in the major scale.

2.2.2 Iconography

Historic visual representations can reveal much about musical instruments from the past. In the case of eighteenth-century horn playing, images provide clues, not only about how the instrument might have been played or held, but also about what sort of horns were in use, including information about aspects of design and manufacture.

As early as the eighth century there is clear evidence of the use of the hand to cover over the bell of the horn, in this case, a simple ivory horn (see Figure 2.1). On the left of this image are two players appearing to cover over the bell of the two short horns they are playing. The two players on the right have longer horns, making it impractical to cover over the bell. Jeremy Montagu suggests that the longer instruments were used for signalling, whereas the shorter horns were used in a melodic context and thus reliant on the extra notes provided by hand-technique [Montagu, 1976, p.13]. He also suggests that this practice may have survived subsequently amongst folk musicians [Montagu, 2007, p.181]. Even at this very early stage in the development of the horn, it seems that musicians were experimenting with the use of the hand in the bell. With the introduction of the more developed form of the horn into the orchestra in the early eighteenth century, it can be assumed that musicians would have been just as curious about exploring the acoustical effects of hand technique as their earlier counterparts.

The majority of iconography from this period however, does not depict the use of the hand in the bell. Figure 2.2 shows a commonly portrayed, open-bell playing position. This image appears on the frontispiece of *The compleat tutor for the french horn*, which Winch refers the reader to when advising on how to hold the horn [Winch, 1746]. There is no written description of a playing position in the text, perhaps to avoid ambiguity. The picture also provides useful additional information about the context in which the horn is being played, in this case, clearly the hunt. The musical exercises included in the tutor are more orchestral in genre which would suggest that in England at this time, the playing posture employed in the context of the concert hall was not so different to that in the field.

Another open-bell playing position is depicted in the engraving shown in Fig-

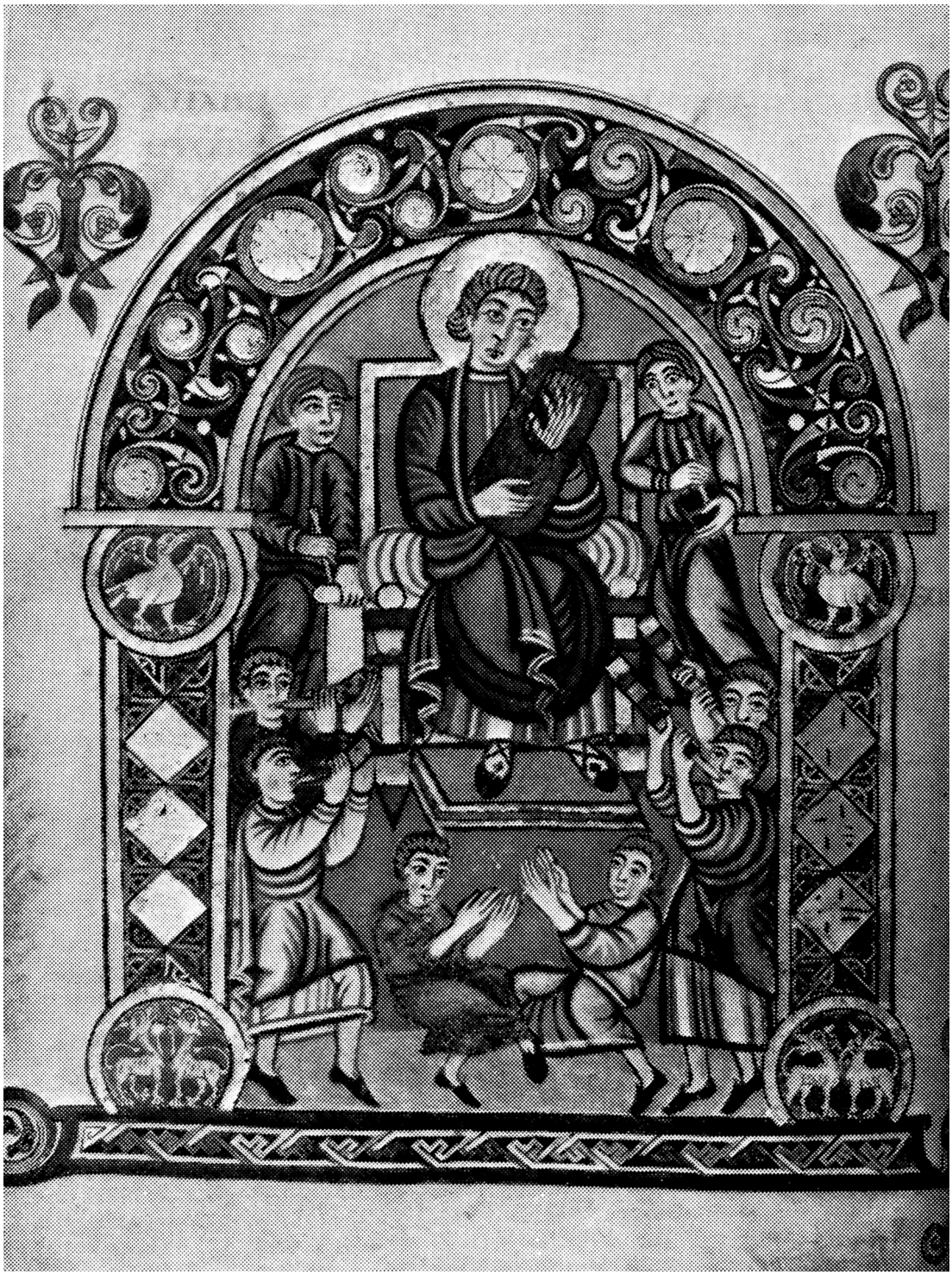


Figure 2.1: Psalter of the eighth century, probably Canterbury. Depicted are two horn players employing an early form of hand technique (bottom left) and two players of longer horns (bottom right) [Montagu, 1976, p.13].

Figure 2.2: Frontispiece from *The compleat tutor for the french horn.* In the text of this book, the reader is referred to this image for how to hold the horn [Winch, 1746].

ure 2.3. In this example the horn players are in Vienna, 1758, rehearsing for the

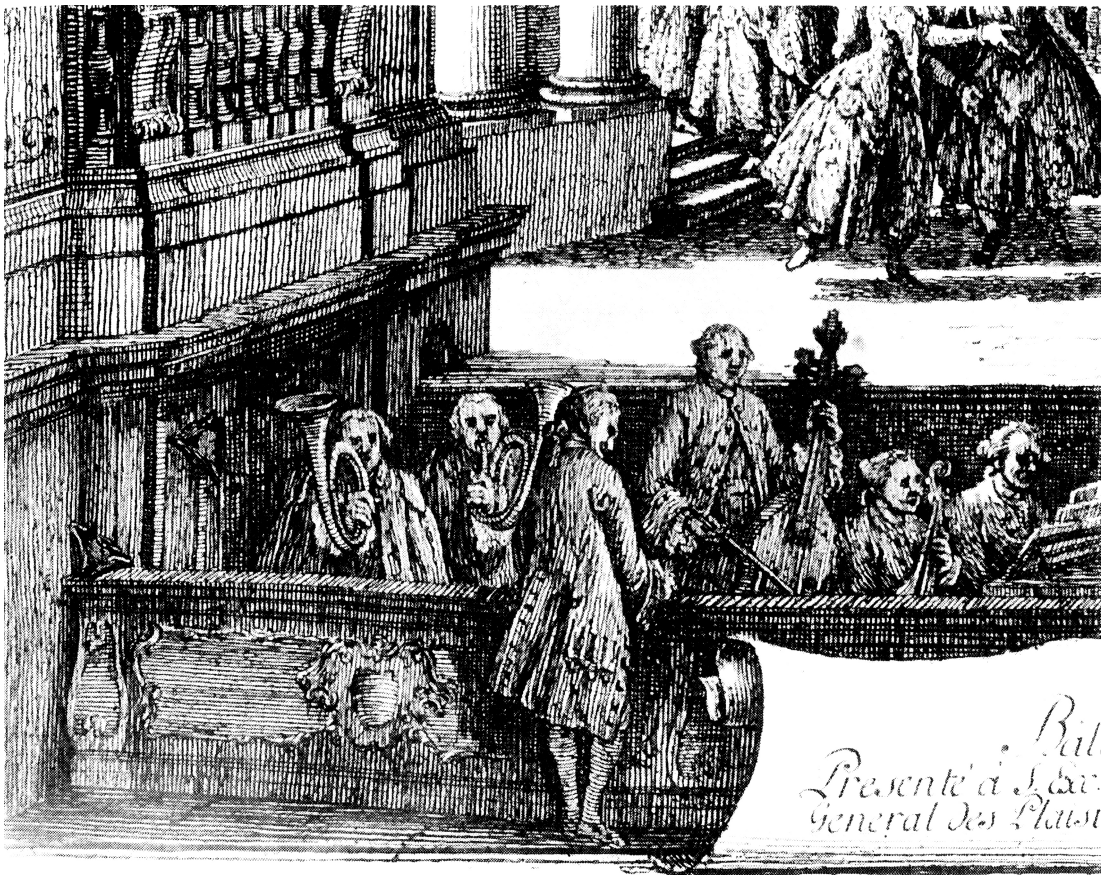


Figure 2.3: Detail from an engraving by Canaletto. Depicted are two horn players in the Vienna Imperial Orchestra playing with their bells up in the air during a rehearsal for the ballet *Le Turc Généreux*, 1758 [Fitzpatrick, 1970, Plate VII (a)].

ballet. The playing position shows the bell directed forwards and up, and is also a commonly found stance in eighteenth-century horn iconography. In practice, this method of holding the horn would be extremely tiring and awkward to sustain for any length of time. Particularly when attempting the high, florid melodies which were becoming an increasingly common feature of baroque horn writing.

Considered from an artistic perspective, the scene looks exciting and lively, and would lose some of its impact if the horn players were to be seated with their bells by their sides. In fact, they might hardly be visible at all behind the wall of the orchestra pit, and so it is likely that Canaletto wanted to reveal the players to their full extent in this work. That is not to say that Canaletto is inaccurate

in his portrayal of the horn players, but perhaps this was only one of a number of ways of holding the instrument, and one of the most pleasing to the eye. A similar playing practice is still encountered to this day, where it is not uncommon for the horn section to be required to stand up with bells held high in the air at the direction of 'bells up' in their horn parts. This is not only for the purpose of acoustical projection, but for the audience's benefit, to make a feature of the horns by providing visual excitement.

The vast majority of images portraying eighteenth-century horn players, show them in the context of the hunt rather than in an orchestral or chamber music setting, but this should not be considered a direct correlation of the horn's sociological significance. It is likely that this bias is attributed largely to the aesthetic appeal of the hunt with all its associated dramatic imagery.

Prioritising aesthetic appeal over faithful representation can sometimes result in pleasing images but technically unrealistic depictions, so care has to be taken when interpreting various iconographical sources. Florence Gétreau raises this point in her article, 'The horn in seventeenth and eighteenth century France: Iconography related to performances and musical works' [Gétreau, 2006]. Here she draws our attention to one particular depiction of a horn player who is holding his instrument in a very impractical manner (see Figure 2.4). Despite this inaccuracy, the painting is still of value, as it suggests the social setting in which the instrument may have been found: a small chamber ensemble. The combination of horn and harp is also interesting to note as it was a popular coupling in the late eighteenth and nineteenth centuries.

Of the limited number of illustrations showing horn players in musical ensembles (as opposed to the the hunt), there are in fact even less depicting the horn player with his hand in the bell. One reason for this might be to do with decisions relating to aesthetic appeal as mentioned previously. Another possible explanation is that the musical scene at this time was still quite exclusive and so painters may have relied to some extent on previous depictions of the instruments for their own works. The portrayal of new techniques and instrument design may have taken slightly longer to filter through to the works of painters and artists.

Figure 2.4: Watercolour by Pierre Antoine Baudoin, *The Concert*, *c*1760. The horn player, said to be the Prince de Soubise, is holding the horn in an awkward and unlikely playing position [Gétreau, 2006, p.62].

A clear depiction of hand-in-the-bell playing technique can be seen in the famous group portrait by Louis Carrogis shown in Figure 2.5. This appears to be a realistic portrayal of a musical gathering from about the 1760s, further substantiated by the fact that the musicians represent five famous virtuosos of the day; the horn player is Jean Joseph Rodolphe. The detail of the horn itself is interesting as it shows a relatively small corpus diameter and long mouthpipe, a design more ergonomically suited to hand technique perhaps.

The horn in Figure 2.6 is not particularly realistic; the approximate shape is evident

Figure 2.5: Louis Carrogis de Carmontelle, between 1760 and 1770. Quartet in the open air showing the horn player using hand in the bell technique [Brüchle & Janetzky, 1976, Plate VII].

but the crook appears to be looped round the corpus of the instrument rather than attached, and the bell has a squashed appearance. The character of this

Figure 2.6: Concert at Charles Burney's house. Engraving by Charles Loraine Smith, 1782; Jacques-Joseph-Toussaint Pieltain is depicted as the horn player [Smith, 1782].

engraving, by artist Charles Loraine Smith, is obviously satirical in nature. The caricatured horn player is known to be Jacques-Joseph-Toussaint Pieltan, a pupil of virtuoso hand horn player, Punto. It is therefore highly likely that Punto would have passed on his expertise in this area of performance to his students, and yet hand technique is not portrayed here. This image may not be entirely reliable as evidence of playing technique but it provides a valuable insight into the link between music and wealth in society at this time.

Another image in which the artist has not been entirely faithful in portraying the crook detail, is the lithograph in Figure 2.7 from the early nineteenth century. The spring-like coiling of the crook in this picture is entirely *unrealistic*, however the rest of the image seems reasonably true to life. The most interesting aspect of this depiction is the setting in which we see the horn being played, in this case a diverse

band of mining musicians.

Figure 2.7: *The Mining Musicians*. Coloured lithograph, 1825 [Brüchle & Janetzky, 1976, Plate XIV]. The horn crook shown here is not a true likeness.

2.2.3 Musical sources

Part of the beauty and nature of music is that it is open to infinite interpretation, yet the written notes can be extremely useful in providing an insight into what instruments are capable of playing, the context in which they might have been played, and even clues as to the technique used to play them. As mentioned previously in Section 2.2, Hiebert has led the way on the topic of analysing eighteenth-century horn writing [Hiebert, 1992, 2006].

It is generally believed that hand horn technique was slower to become established in England than in the Germanic lands, not being fully embraced until the arrival of the two virtuosos, Punto and Spandau, to London in the early 1770s. This theory has been questioned by Hiebert after he undertook a close examination of horn parts from the Egerton Manuscript Collection, thought to be dated from around the mid-eighteenth century [Hiebert, 2006]. The Egerton collection is currently housed at the British Library in London and contains some of the earliest examples of orchestral writing in England, including twenty nine sets of manuscript parts from symphonies and concertos by various composers [various, 18th century]. Some of the horn writing is quite advanced for its time, requiring the player to produce non-series tones. The easiest method of obtaining these notes would have been to employ some form of hand technique. Figure 2.8 shows an example of such innovative writing.

Figure 2.8: *Grave* from a concerto by Carlo Vernsberg. Egerton Collection, No. 17 [Hiebert, 2006, p.245].

In this excerpt, Carlo Vernsberg calls for non-series tones in the middle register of the horn, as illustrated in the last two bars of Figure 2.8, e.g. written A and F♯. It was not entirely uncommon for composers to include notes such as these in their compositions in the early eighteenth century, but the context in which they most frequently appeared was either as a passing note, or in a part which was doubled by another instrument. In this example, not only are the A and F♯ not passing notes, but they are integral to the harmony during the final cadence of this movement, and occur on the strongest parts of the bars. Vernsberg was obviously pleased with the musical effect of this passage, for he uses it at least twice more in his works. Hand technique is the most obvious solution to getting these notes, but another method used to alter the pitch of notes is to change the embouchure, a technique known as lipping. In the case of these middle register notes, A and F♯, pitch manipulation using embouchure alone would be extremely difficult, a practice more suited to low playing.

The crooks used in solo horn writing are normally D, E♭, E or F, chosen for their pleasing timbral quality and also for their ease of articulation, yet in this movement (Figure 2.8), Vernsberg writes for horn crooked in C-basso, a much more unusual decision. One advantage of using such a long crook as this, is that hand technique is more sensitive than on a shorter crook, i.e. the longer the crook, the more effective the hand is in lowering the pitch [Merewether, 1978]. This results in a more even tone quality and may have influenced Vernsberg's choice of crook for the slow movement in which ease of articulation is less of a concern given the more sedate tempo.

Analysis of horn writing from the court of Dresden during the mid-eighteenth century has revealed that the majority of non-series tones are to be found in the second horn parts, and at the lower end of the range, see Figure 2.9, lower line. This is most likely because it is easier to alter the pitch of a note using embouchure manipulation (lipping) in the lower register of the horn than in the high register, as mentioned previously. Low horn parts which include only the natural resonances of the instrument are greatly restricted due to the widening intervals with decreasing pitch, and so innovative composers and able musicians would have wanted to find ways round this.

Figure 2.9: Concerto for Violin (1740). First movement, *Allegro*, by F. Benda / J.G. Pisendel, bars 13-14 [Hiebert, 1992, p.154].

The second horn writing in Figure 2.9 is extremely virtuosic, demanding great flexibility and control. This is the earliest example of such a technically demanding low horn part form the Dresden manuscript collection, possibly also from throughout the Western world [Hiebert, 1992]. The composition is thought to have been a joint venture, the majority written by Franz Benda who left the top two staves free for the later addition of horn parts by Johann Georg Pisendel.

The talented second horn player whom Pisendel was writing for was most likely Hampel who was resident at the court at the time of composition in 1740. The very same Hampel who is strongly associated with the establishment of hand technique. Pisendel may have been writing with the specific skills of Hampel in mind. Lipping has already been mentioned as a plausible method for playing some of the low, non-series tones, but this method is most easily accomplished when approached by step from a nearby natural resonance. A number of the notes in this excerpt (Figure 2.9) are further away from a natural tone and furthermore, approached by a leap. In these cases, some form of hand technique may have been used to aid the work of the embouchure, particularly given Hampel's association with experiments in hand technique [Hiebert, 1992].

An interesting case in the discussion of embouchure versus hand technique is brought to light in a later work by Joseph Haydn, composed in 1782. A page from the autograph score of the opera *La fedeltà premiata* clearly shows the direction '*Solo con Sordino*' above the first horn part (Figure 2.10), but Haydn includes the slightly wayward eleventh and thirteenth natural resonances in this horn melody: the written F and A. These notes normally require some kind of pitch adjustment to be brought in to tune but conventional hand technique must be ruled out in this instance due to the requirement of a mute in the bell, despite the fact that

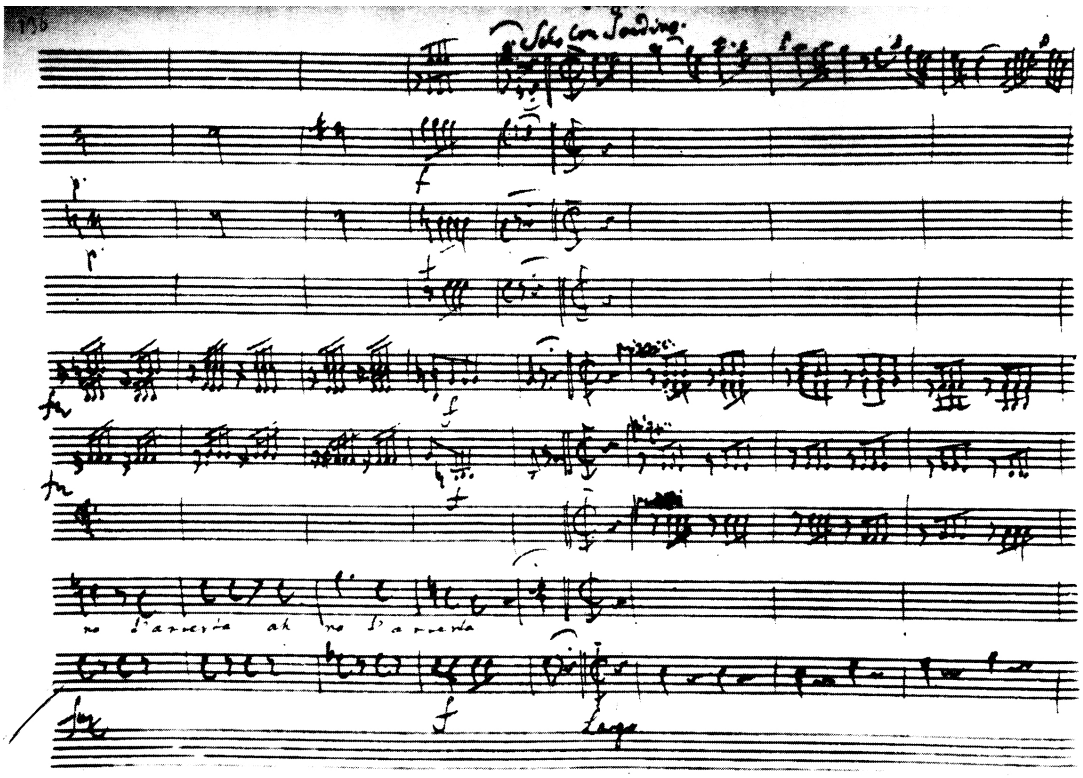


Figure 2.10: *La fedeltà premiata*, (1782) by Joseph Haydn. A page from the autograph score showing part of Celia's Aria in Act I, 'Deh soccorri un infelice', *Largo*; the top line shows the muted solo horn part [Landon, 1978]

hand technique had, by this stage in the eighteenth century, become firmly established.

There are several potential solutions to this conundrum; Stephen [2010] suggests that this excerpt is evidence that either the notes were left unaltered, or that lipping was still employed at this late stage in the eighteenth century. Morley-Pegge [1960, p.136-7] on the other hand, seems certain that horn players of the eighteenth century would have used a special adjustable mute, allowing the pitch to be altered by means of a rod or cord attached to the wide end. It can also be ruled out that this instruction was merely wishful thinking on the part of Haydn, because there is evidence to suggest that not only was the muted effect heard in public, but that it was performed well and was thought to be a pleasing effect; after hearing a performance of the piece at a concert in 1783, a contemporary reviewer

commented specifically on the 'striking and surprising' nature of the echo produced by the muted horn, and hoped that composers would write specifically with that effect in mind [Landon, 1978, p. 539].

Hand technique is thought to have become established in the eighteenth century, partly due to increasing desire for improved intonation when the horn entered the orchestra, but also in order to extend the range of notes available to the player, allowing composers to experiment with much greater chromaticism in their writing. There is also evidence to suggest that composers were keen to experiment with colourful timbres through the effect of hand-stopping; Georg Philipp Telemann was extremely innovative in his day and in one of his works, the *Alster Overture*, he employs a whole host of humorous and colourful instrumental effects, see Figure 2.11.

Figure 2.11: *Die concertirenden Frösche Krähen*, by Georg Philipp Telemann. From his Overture (Suite) in F, the *Alster Overture*, bars 18-22 [Telemann, 1995].

This piece of music was written sometime after 1721 and features four horns. The excerpt in Figure 2.11 is from the movement, aptly entitled, *Die concertirenden Frösche Krähen* ('The Concert of Frogs and Crows'). It is evident from the style of writing, that Telemann enjoyed experimenting with interesting timbres and harmonies; the horn parts are highly chromatic and at times extremely dissonant.

Passages, such as bars 19-21 (see Figure 2.11) in horn parts one and two, are particularly effective when hand-stopping is employed to certain notes, thus recreating the croaking and crowing of the animals named in the title. The bright and brassy characteristic of hand-stopped notes would be extremely well suited for this effect.

2.3 Alternative approaches

The majority of research about the early horn is based on evidence from archival documents, iconography and manuscripts but these are not the only useful sources of information. The rest of this chapter looks at various approaches which have not yet been fully exploited in this field. The line where science and art meet is still often seen as a barrier, due in part to the polarisation of these two spheres, but through interdisciplinary research, incorporating elements from a number of different disciplines, it is possible to gain a broader insight into the topic at hand.

2.3.1 Acoustics

An early example of interdisciplinary horn research can be found in an article published in the *Proceedings of the Musical Association* in 1909 by the acoustician David James Blaikley [1909]. In his article, 'The French horn', Blaikley explores the development of the early horn with the insight of a scientific mind, focussing on the controversy surrounding the change in pitch when hand technique is employed. From his description, the matter is still not entirely clear and there have been many further discussions on this topic in the intervening years. Whereas Blaikley [1909, p.127] attributes the effect of hand-stopping to the instrument becoming more cylindrical in shape, research since [Backus, 1976; Pyle, 1964] has shown that the situation is more complex, involving the hand as a 'lumped resonator'. Further forays into the history of the horn involving acoustical insight have been carried out by Robert Pyle [2000; 2006] and Jonathan Kemp *et al.* [2007], however this is still an area with much potential for cross-collaboration.

Many historic musical instruments are too fragile to be played and the only evidence that exists of what they might have sounded like are descriptive accounts from audience members at the time. But accounts are subjective, and words have a limited capacity to express the subtleties of music and sound. This is where acoustical analysis has the potential to provide additional insight.

Techniques such as measurement of the acoustic impedance of a brass instrument [Widholm, 2001], allow evaluation of aspects such as the Q factor [Smith *et al.*, 2007] and intonation [Bertsch, 1998], which in turn can provide information about what a brass instrument might sound like and feel like to play [Moore, 2002]. Further acoustic tests concerning the brassiness potential of an instrument [Myers *et al.*, 2012] and the spectral content of a note [Poirson *et al.*, 2005] can also be carried out without the need to involve a human player. All of these acoustical tests require minimal contact with the instrument, but where acoustical measurements are not possible due to damage, there is also the potential for results to be predicted using a computational model with detailed bore profile measurements as the input [Caussé *et al.*, 1984]. Experiments such as these provide a useful set of tools with which to explore the sound and playing characteristics of early horns which are no longer in a condition to be played.

2.3.2 Ergonomics

Despite the field of ergonomics being multidisciplinary by its very nature, incorporating elements from areas such as engineering, psychology and graphic design, it is surprising that there are so few examples of object design considered retrospectively, in a historical context. One example involving ergonomic analysis of historic artefacts, explores differences in eighteenth-century axe design [Corrigan *et al.*, 1981], and is based on experimental testing, an approach which could be useful to apply to historic musical instrument research. Keyboard instrument layout has been the subject of some systematic ergonomic analysis in an attempt to predict fingering options [Jacobs, 2001] but the historic significance of these results has only briefly been touched on. Currently, there does not appear to be any systematic research linking the design and playing technique of early horns, despite the issue

surrounding the location of the hand making this an appealing avenue.

Determining a comfortable playing position for the right hand in the bell of the horn is a key starting point in this discussion on ergonomics, and there are several articles which discuss, in general terms, the 'normal working area' of the arms [Das & Grady, 1983]. A step on from this are the studies which include sets of experimental data from human strength testing. These are numerous and cover all aspects of muscle strength for various limbs and postures, measuring both static and dynamic actions, whether lifting, pulling or pushing [Mital & Kumar, 2000].

Most relevant to horn playing are the papers focussing on a lifting force of the arm in various positions [Kumar & Garand, 1992]. Based on experimental data such as this, predictive equations have been calculated for different scenarios [Mital & Manivasagan, 1984]. One relevant article includes a predictive equation based on experimental data measuring the maximal force of the arm when lifting in twenty-four different postures [Roman-Liu & Tokarski, 2005]; a potentially useful and objective approach for predicting which horns might be comfortable to hold with the hand in the bell.

2.3.3 Manufacture

There is still very little known about the craft of brass instrument makers in the eighteenth century due to a dearth of documentary evidence from this period. Combining what evidence there is, with signs of construction marks on the instruments themselves, and an in depth knowledge of working with brass and metal, Robert Barclay [1992] tackles this topic head on in his book, *The Art of the Trumpet Maker*. Another highly informative book which traces the development and manufacture of the trumpet and related instruments in great detail, is *Instruments of the Single Harmonic Series*, Volume 1 of *Trumpets and other high brass* by Sabine Klaus [2012].

However, there are design challenges particular only to horns, such as wide bell flares and very long sections of curved tubing. The eighteenth century was a pe-

riod of great change in terms of horn design and while Arnold Myers [2006] has carried out an interesting study comparing the design and acoustics of a number of early hunting and orchestral horns, no-one has yet undertaken a wide-ranging and systematic survey of early horn design and manufacture.

The approaches adopted in smaller scale studies have the potential to be useful on a much larger scale. For example, bore profile comparisons have proven insightful for exploring the often blurred boundaries surrounding brass instrument classification and taxonomy [Myers, 2012; Myers *et al.*, 2005; Sharp *et al.*, 1995, 1997]. One instrument in isolation has limited potential for telling the story of its development but with the collective data from many instruments, its history becomes clearer.

Herbert Heyde has adopted a systematic approach to instrument research and has gathered together an impressive body of detailed measurements from many different types of brass instrument across Europe. The information forms part of the museum catalogues for collections in Eisenach, Frankfurt an der Oder, Halle and Leipzig. In the Leipzig catalogue which concerns horns, Heyde includes a number of interesting graphs comparing detailed measurements of particular sections of tubing [Heyde, 1982]. Also included are intricate drawings of manufacturing details such as stays, ferrules, garlands (also photographs), etc., useful for identifying instrument makers and possible repair work.

2.4 Summary

Contemporary evidence in the form of archival documentation (tutors, paintings, manuscripts, etc.) can provide valuable information about eighteenth-century horn making and playing, despite the evidence seeming contradictory at times.

Written sources in the form of tutors and methods are conspicuously lacking in information about playing technique, and accounts from English concert goers in the late eighteenth century appear to recount both pleasure and distress on

hearing the effect of hand technique by famous foreign virtuosi, perhaps for the first time.

Iconographical materials have been shown to reveal some largely impractical playing positions and designs, and overall tend to favour the view that horns were mostly played with bells up, employing no hand technique. However, it is probable that some of the more vertical playing positions portrayed were perhaps used mainly for special effect in the same way that modern horn players are sometimes asked to raise their bells, not only for reasons of sonority, but also to create visual excitement.

Manuscripts from the eighteenth century clearly show examples of notes which require some form of pitch alteration in order to bring them in to tune. The highly virtuosic and innovative writing from the first half of the eighteenth century at the court of Dresden reveals that the resident musicians were technically far in advance of players elsewhere in Europe, and it is likely that this is where hand technique first flourished. A recent discovery of innovative horn writing in England is worth noting because it suggests that, in this region too, players were perhaps experimenting with the use of the hand in the bell earlier than previously thought.

But this type of research has its limitations. These sources offer historical snapshots from various sociological perspectives, whether teacher, painter, member of public, or composer, and as such the information which reaches us has already undergone some degree of interpretation.

Sound in particular is extremely subjective and difficult to describe, but experimental methods used in the field of acoustical research can provide a more objective approach and a different angle. The ideas and techniques involved in ergonomic design and analysis have not yet been explored in the context of early horn technique, yet the positioning and comfort of the right hand in the bell of the horn must have been of concern to eighteenth-century makers. The development of the horn has been influenced by both musical factors such as tone quality, and also practical aspects such as playing technique. These changes can be traced through subtle variations in the design of the instrument, such as the shape of the bore profile, but very few studies have attempted to explore these subtle changes in

any detail. Science provides a more objective approach to research and has great potential in the field of organology; empirical testing and systematic analysis can be carried out on large groups of musical instruments, making them a key source of their own history.

Herbert Heyde suggests that there are two different branches of organology: systematic and historical [Heyde, 2001]. This divide can partly be explained by the dual nature of instrument evolution and development, reflecting both the cultural and physical aspects of its design. This divide is also apparent in the review of literature concerning the early horn, however the current state of research shows a definite bias towards the historical rather than the systematic (scientific) approach. Inspired by a desire to create a more balanced approach to early horn research, and also to cross the divide between the world of art and science, this thesis will concentrate on techniques of systematic analysis, but with reference to the vast body of valuable historical research already undertaken.

Chapter 3

Sound

The timbral quality known as 'brassiness' is the subject of this chapter. The importance of this tonal characteristics as a key identifier of brass instrument type is first discussed (3.1), followed by a section looking at why brassiness occurs (3.2). The methods by which timbral variation can be measured (3.3) and the results from such experiments (3.4) make up the next sections, followed by a summary of the conclusions and avenues for further work (3.5).

3.1 Introduction

The primary function of any musical instrument is to produce sound. Our museums are filled with historic instruments, many of which no longer have the capacity to produce the music they once did, either because they are damaged or because they are too fragile to be played. The number of unplayable instruments is only going to increase with the passage of time, so it is vital that new ways are found to assess the playing characteristics of these museum objects, without detriment to their current condition. Non-invasive acoustical testing is useful for this purpose and can provide a new perspective on historic musical instrument research.

Over the years our taste for different musical sonorities and styles has changed, and this is reflected not only in the kind of music we listen to, but also in the

development of historic musical instruments. Brass instruments, for example, used to have a lighter and brighter sound quality in the baroque and classical eras, well suited to the type of music they were required to play, but with the change in mood of the romantic nineteenth century, expanding orchestras and bigger soundscapes meant that brass instruments had to adjust accordingly. This resulted in the production of instruments with generally larger bore diameters which were capable of producing a full, round sound without the tone becoming too brassy, too early in the dynamic range. But what does 'brassy' actually mean and can it be measured? These are important questions, particularly for musicians interested in trying to recreate the sounds of brass instruments from the past, but also for organologists looking to trace their tonal history through the ages.

3.1.1 Defining brassiness

Words such as 'brighter' and 'brassy' are often used by musicians in an attempt to describe the 'timbre' of an instrument, or what it sounds like. Used in this context, these terms are considered subjective, because they refer to how a listener might perceive a sound and these qualities can not easily be measured. More recently however, acousticians have found a way of measuring a defining feature of the timbral quality known as 'brassiness'. This has led to two slightly different meanings of the word 'brassiness', as both a subjective (perceived) and objective (measured) quality.

Brassiness can be described as a change in timbre with increasing dynamic level, brought about by an increase in the strength of higher frequency components in the radiated sound. It is also sometimes referred to as spectral enrichment and occurs mainly as a result of non-linear behaviour of the sound wave in the air column of the instrument. The rate at which spectral enrichment occurs during a crescendo on a brass instrument is a key identifier to the listener of the type of instrument being played. Brass instruments have a wide dynamic range, and the change in timbre that can be heard between quiet and loud playing is striking. At the loud end of the dynamic range, the tone of the instrument is often described as brassy or *cuivré*.

The onset of brassiness is not a sudden event, it is a gradual process which occurs at a faster or slower rate depending on the dimensions of the instrument in question. For example at loud dynamic levels, trombones, which have predominantly cylindrical bore profiles, generally sound brassier than tubas, which are more conical in shape. Researchers have attempted to both predict and measure this phenomena using two main methods.

Initial research into the brassiness characteristic focussed mainly on the development of a predictive equation called the brassiness potential parameter, B [Pyle & Myers, 2006] (see Section 3.2.1 for more information). Values of B are calculated based solely on measurements of the bore profile and have been found to be very successful in distinguishing between the different families of brass instruments for taxonomical purposes [Gilbert *et al.*, 2007]. Researchers have also looked more specifically at the timbral implications of using different valve combinations on chromatic brass instruments [Myers *et al.*, 2010a] and at comparing very similar types of instrument such as Wagner tubas and cornophones [Norman *et al.*, 2010b].

A second (experimental) method for exploring brassiness potential, involves measuring the spectral enrichment of the radiated sound during the course of a crescendo (increase in dynamic level). Tests have been carried out using both human players [Myers *et al.*, 2007] and loudspeakers [Myers *et al.*, 2010b] as inputs to the instrument and the results compare favourably, not only between the two experimental methods, but also with the theoretical brassiness potential parameter [Myers *et al.*, 2012] already mentioned.

Brassiness characteristics have been shown to vary significantly between categories of brass instrument, but even within one type (for example the horn), musicians are sensitive enough to be aware of the specific playing characteristics of different models of instrument. They may have a preference for the ease of articulation on one instrument, or perhaps favour the intonation on another, but certainly one of the most important playing characteristics to a musician is the tone quality, and how it varies with increasing dynamic level. Instrument preferences have changed over the years and it is interesting to explore this by looking at horn design in combination with acoustical measurements of spectral enrichment, a good indicator

of brassiness.

3.1.2 Historical context

Arguably, the most significant change in the development of the horn occurred with the invention of the valve at the beginning of the nineteenth century. This had major repercussions in terms of the sound quality of the instrument and as a result, divided the horn playing community. Prior to the invention of the valve, horn players were required to alter the length of their instrument through the substitution of different lengths of tubing (called crooks), in order to play in different keys. It may seem surprising therefore, that the invention of the valve was not welcomed warmly by all horn players, keen to find a solution to the problem of quick changes of key.

In France in particular, the crooked horn remained a popular and often preferable choice throughout the nineteenth century. One reason for its longevity was the desire to retain the specific timbral colours associated with different crooks; when playing music at the same pitch, the longer crook lengths such as C and B$^{\flat}$ basso produce a rich, brassy tone compared to the shorter crooks such as A. This tonal variation can be explained due to the brassy effect of non-linear wave steepening in the cylindrical sections of the tubing on the instrument [Hirschberg *et al.*, 1996]. The initial reluctance of many musicians in the nineteenth century to embrace the new valved horn with its arguably more homogenised tone quality sparked the idea for this chapter: an investigation the brassiness potential of various horns. Just how wide ranging are the tonal characteristics of the various crooks, and how has horn timbre changed over the years?

3.2 Theory

Brassiness occurs due to non-linear behaviour of the pressure wave as it travels along cylindrical sections of the instrument [Hirschberg *et al.*, 1996]. The effect is

negligible at low acoustic pressure levels, but becomes increasingly important as the acoustic pressure increases, for example, when playing at very loud dynamic levels. This non-linearity causes higher frequency components of the sound to become strongly excited which the listener then hears as a bright and brassy timbre. The dominant factor influencing the potential of an instrument to produce a brassy sound, is the bore profile. Other factors have also been cited as having a small effect on this aspect of timbre; mouthpiece dimensions [Poirson *et al.*, 2005], construction material of the instrument [Pyle, 1998, 2009] and the technique of the player employing embouchure manipulation [Norman *et al.*, 2010a].

A horn consists of both cylindrical and expanding sections of tubing. As mentioned already, spectral enrichment due to non-linear behaviour in the air column of the instrument occurs readily in long cylindrical sections of tubing. The front of the pressure wave becomes steeper as it travels along these sections of tubing and has the potential to develop into a shockwave. The acoustic pressure decreases however, as the wave travels through expanding sections of tubing and therefore, in order to achieve similar levels of non-linear distortion in expanding sections, the sound must travel along a greater length of tubing. This can be described by the following coordinate stretching function *z(L)* [Norman *et al.*, 2010a]:

$$z(L) = \int_0^L \frac{D_0}{D(x)} dx, \tag{3.1}$$

where D_0 is the minimum diameter in the mouthpipe of the instrument, $D(x)$ is the diameter at a distance x along the axis of the instrument, and L is the overall length of the instrument. The value of $z(L)$ is the equivalent length of cylindrical tube, of diameter D_0, in which the same degree of non-linear steepening occurs as in the actual instrument of total length L.

3.2.1 Calculating brassiness

Based solely on measurements of the bore profile of an instrument, the brassiness potential parameter B can simply be defined as the ratio of the equivalent cylin-

drical length $z(L)$ (for the occurrence of non-linear propagation) to the equivalent conical length L_{ecl} [Gilbert *et al.*, 2007]:

$$B = \frac{z(L)}{L_{ecl}}, \tag{3.2}$$

where $z(L)$ is the maximum stretched coordinate value from Equation 3.1, and L_{ecl} is the equivalent length of a cone, with a fundamental frequency which corresponds to the nominal pitch of the instrument in question.

The value of the brassiness potential parameter for any typical brass instrument will always fall somewhere between zero and one. Instruments such as trumpets and trombones, which have long cylindrical sections of tubing, have a higher value of B than more conical-shaped instruments such as Wagner tubas and euphoniums.

Based on experimental results, brassiness can also be analysed by comparing a parameter called the normalised spectral centroid SC as defined by Beauchamp [1982]:

$$SC = \frac{\sum_n nP_n}{\sum_n P_n}, \tag{3.3}$$

where P_n is the pressure amplitude of the nth harmonic component in the radiated sound. The spectral centroid is a measure associated with the brightness of a sound and is a calculation of the weighted mean of the harmonics present in the signal, where the weighting corresponds to the magnitude of the pressure amplitudes P. It can be likened to the 'centre of gravity' of the tone. See Figure 3.1 for a simplified theoretical diagram to illustrate this point.

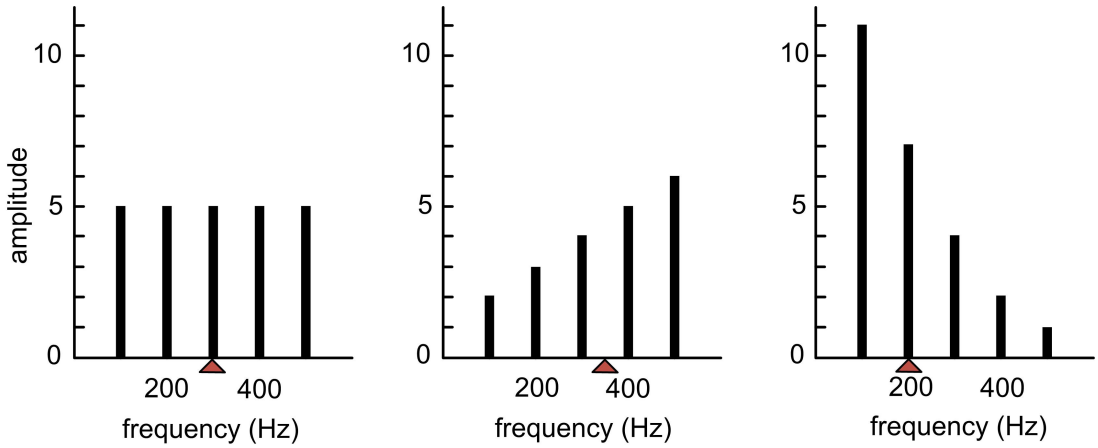


Figure 3.1: Diagram showing the spectral centroid weighting (red triangle) for three simplified harmonic spectra. The graph on the left shows a spectral centroid value of 300 Hz, the graph in the middle, 350 Hz, and in the graph on the right, 200 Hz.

3.3 Methods

The two experimental methods for assessing the potential brassiness of an instrument include either the use of a human player or a loudspeaker, in both cases to generate a crescendo. Using musicians introduces an element of human control and a certain degree of subjectivity to the results. Excitation of the instrument using a loudspeaker on the other hand, has several benefits. The approach is non-invasive, requiring minimal handling of the object, a factor particularly advantageous in the case of historic brass instruments where playing can increase the risk of corrosion. The loudspeaker is also able to produce repeatable and unambiguous amplitude sweeps, leading to clear, well defined results which correspond well to the player's perception of brassiness. For these reasons, a loudspeaker was used to generate the input signal to the instruments in the following set of experiments, rather than a human player.

3.3.1 Non-invasive approach

The input sine wave crescendo generated by the loudspeaker, lasting five seconds, was measured at the entrance to the instrument using a 106B PCB Piezotron-

ics dynamic pressure transducer, and the resulting radiated pressure signal was measured in the plane of the bell of the instrument with a Brüel and Kjær 4192 condenser microphone. A frequency of 1500 Hz was chosen as a suitable value for the input sine wave signal because it is higher than the predicted cut off frequency for horns, thus ensuring that relatively little reflection occurs at the bell of the instrument, but also low enough to avoid distortion of the waveform due to the excitation of higher order modes. The maximum pressure amplitude range was predetermined based on safe limits of the loudspeaker cone. The experiments were carried out in an anechoic chamber and a schematic of the set up can be seen in Figure 3.2.

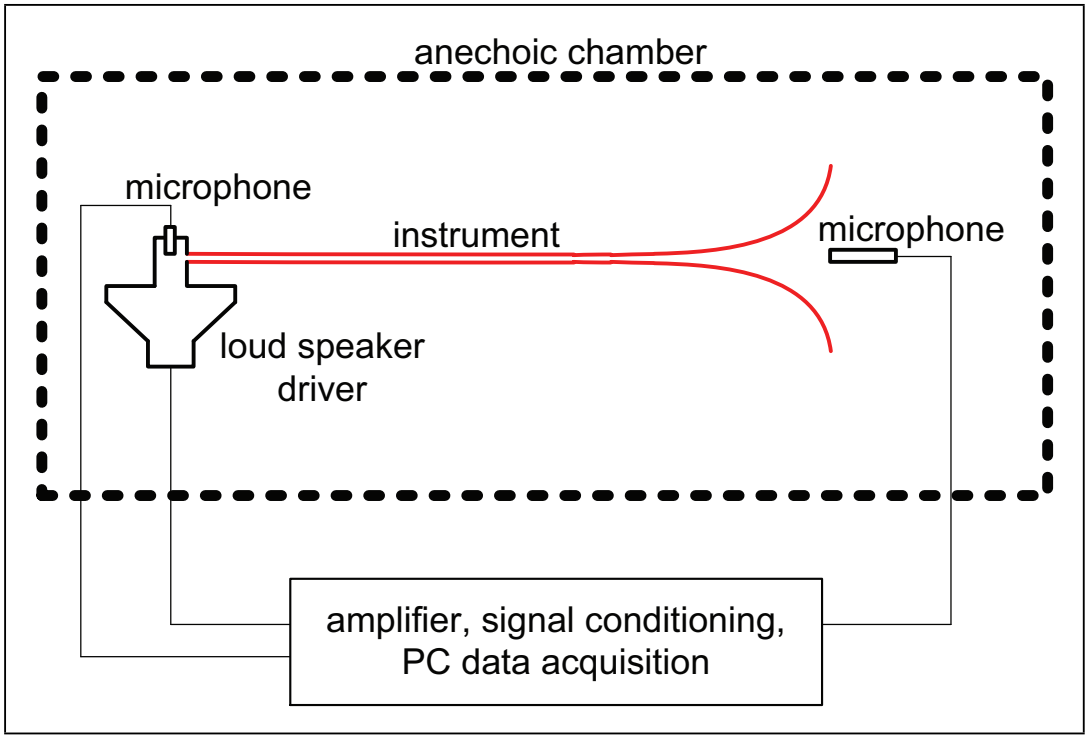


Figure 3.2: Diagram of the experimental set up to test brassiness, showing the positions of the various pieces of equipment.

The relationship between the spectral content of the input and output signals over the course of a crescendo provides useful information about the extent of spectral enrichment with increasing dynamic level in the air column of a particular instrument. Spectral centroid values were calculated for both pressure signals and give

a good indication of how bright the output tone sounds [Martin & Kim, 1990] (see Section 3.2.1). The output spectral centroid values were then plotted as a function of the RMS input pressure signal in order to create brassiness curves (see Figure 3.3). An instrument with very little brassiness potential would produce a curve with minimal increase in the output spectral centroid value (e.g. a serpent or a tuba), whereas the final spectral centroid value for a brighter sounding instrument such as a trombone would be much higher. Orchestral horns fall somewhere in between these two extremes.

3.4 Results

The following discussion provides an initial exploration into the extent of timbral variation amongst a selection of ten orchestral horns. The data set spans a wide historical period, including simple coiled instruments from the early eighteenth century when horns first entered the orchestra, and also their modern counterpart used today, a valved double horn. Concerning the early, natural horns, experiments were carried out using the crooks D, F and A, representing a commonly used low, medium and high pitch crooks. For the sake of comparison, the appropriate valves were depressed on the modern horn in order to produce the same nominal length of instrument.

3.4.1 Differences

Different crooks have different tonal characteristics, one of the attractions of the early orchestral horn as was mentioned in the introduction, Section 3.1.2. Of the crookings measured, D was commonly the brassiest and A the least, with F falling somewhere in the middle, see Figures 3.3-3.6.

These results are to be expected since the D crook (or length of instrument in the case of the modern horn) has the longest section of cylindrical tubing, allowing for the greatest build up of non-linear behaviour in the air column of the instrument.

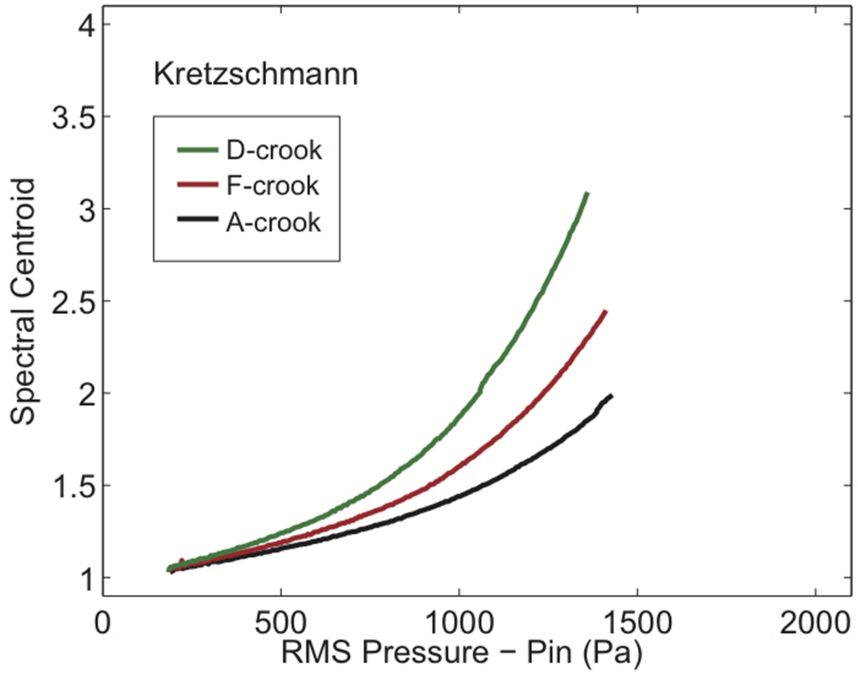


Figure 3.3: Brassiness curves showing the variation in spectral centroid with increasing pressure for a horn by the maker Kretzschmann (GB.E.u, 531). Comparison of crooks D (green), F (red) and A (black).

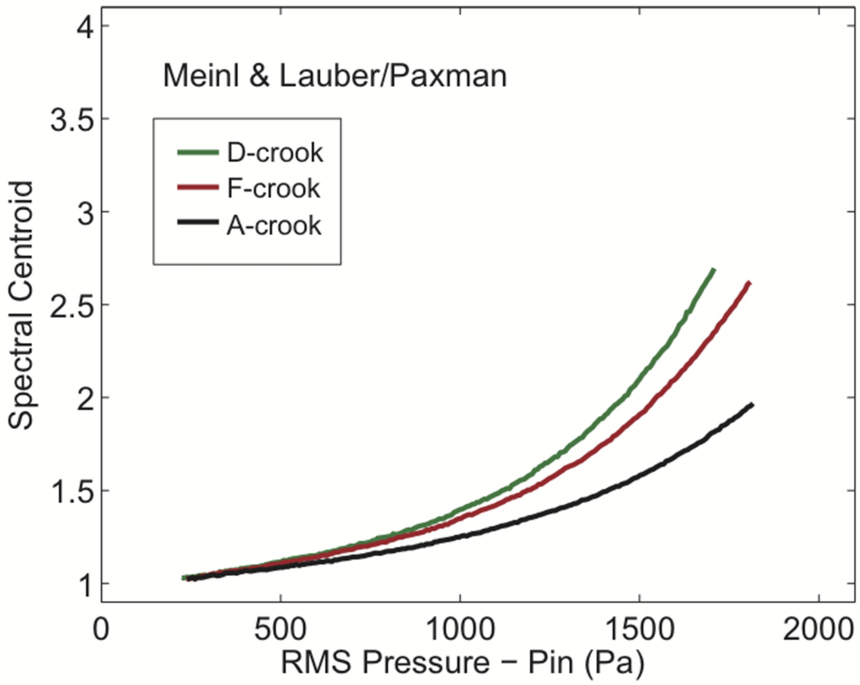


Figure 3.4: Brassiness curves showing the variation in spectral centroid with increasing pressure for a horn by the makers Meinl & Lauber / Paxman (GB.E.chick, 2008.1). Comparison of crooks D (green), F (red) and A (black).

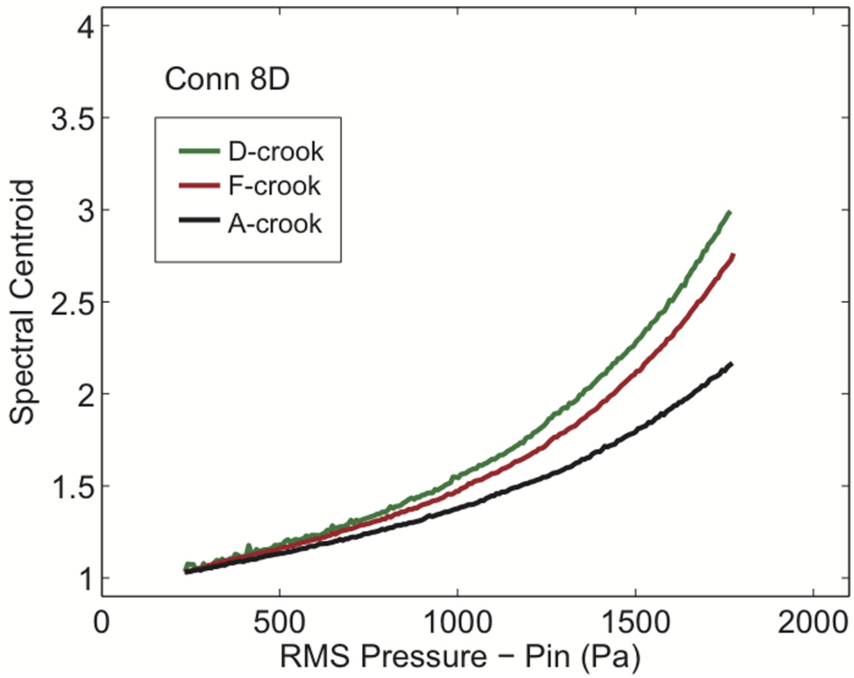


Figure 3.5: Brassiness curves showing the variation in spectral centroid with increasing pressure for a horn by the maker Conn (GB.E.chick, 2007.3). Comparison of crooks D (green), F (red) and A (black).

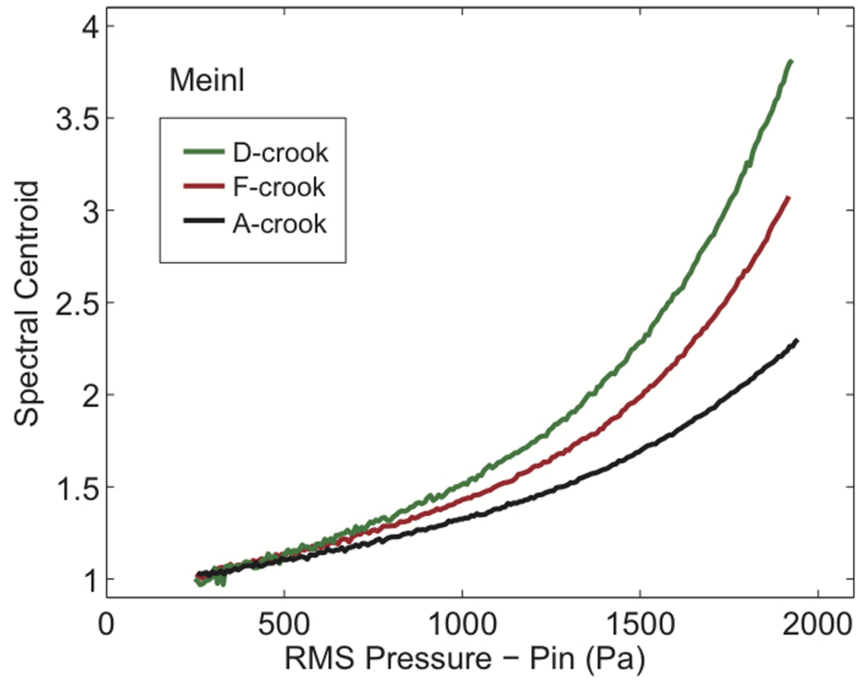


Figure 3.6: Brassiness curves showing the variation in spectral centroid with increasing pressure for a horn by the maker Meinl (GB.E.chick, 2004.2). Comparison of crooks D (green), F (red) and A (black).

The consistency concerning the order of the brassiness curves for each instrument is also not surprising since these timbral differences are significant enough to be felt by the player but also heard by the listener.

When the brassy curves were grouped according to pitch (D, F and A respectively), the order in which the horns appeared within each crook grouping was also reasonably consistent. Figures 3.7 and 3.8 show this pattern in the crook comparisons of D and F for three instruments. This shows that the timbral characteristics of a particular instrument are likely to be retained, even when changing crook, i.e. an instrument which has a higher brassiness potential on one crook than another instrument, will show similar characteristics regardless of the length of crook being compared.

The Kretzschmann (GB.E.u, 531) clearly has the greatest potential for brassiness but perhaps more interestingly, the Meinl & Lauber / Paxman (GB.E.chick, 2008.1) and the Jiráček (GB.E.chick, 2003.1) start out with similar brassiness characteristics for both F and D crookings, but after 1000 Pa, the brassy curves for the Meinl & Lauber / Paxman diverge and the rate of spectral enrichment increases more rapidly.

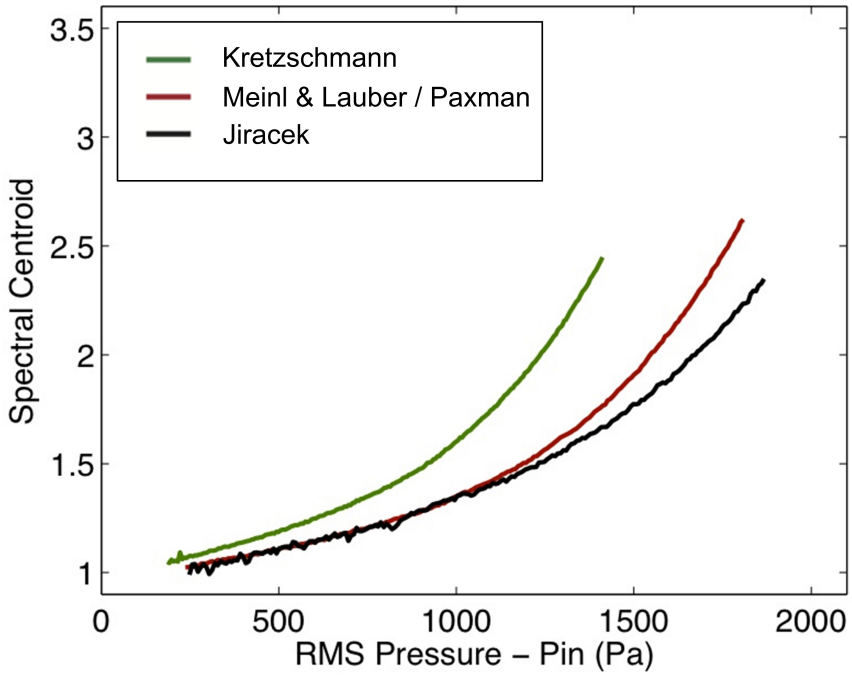


Figure 3.7: Brassiness curves showing the variation in spectral centroid with increasing pressure for three horns crooked in F by the makers Kretzschmann (GB.E.u, 531), Meinl & Lauber / Paxman (GB.E.chick, 2008.1), and Jiráček (GB.E.chick, 2003.1).

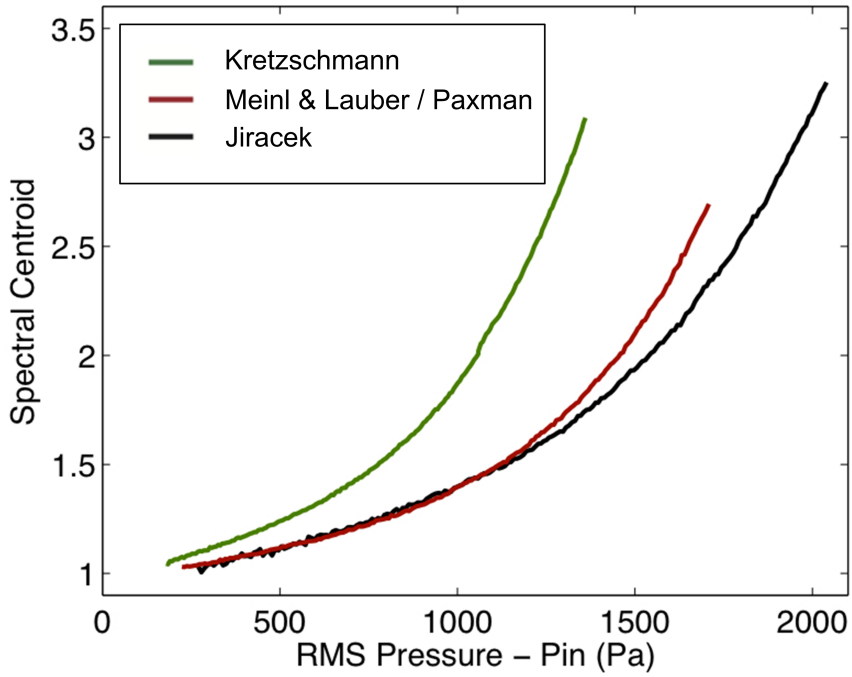


Figure 3.8: Brassiness curves showing the variation in spectral centroid with increasing pressure for three horns crooked in D by the makers Kretzschmann (GB.E.u, 531), Meinl & Lauber / Paxman (GB.E.chick, 2008.1), and Jiráček (GB.E.chick, 2003.1).

3.4.2 Similarities

Conspicuous by their similarity are a group of four horns from the end of the eighteenth and beginning of the nineteenth centuries, all crooked in F by makers Uhlmann, Kretzschmann, Courtois, and an anonymous craftsman. Figure 3.9 shows the brassiness curves from these four horns in isolation. It is uncertain why

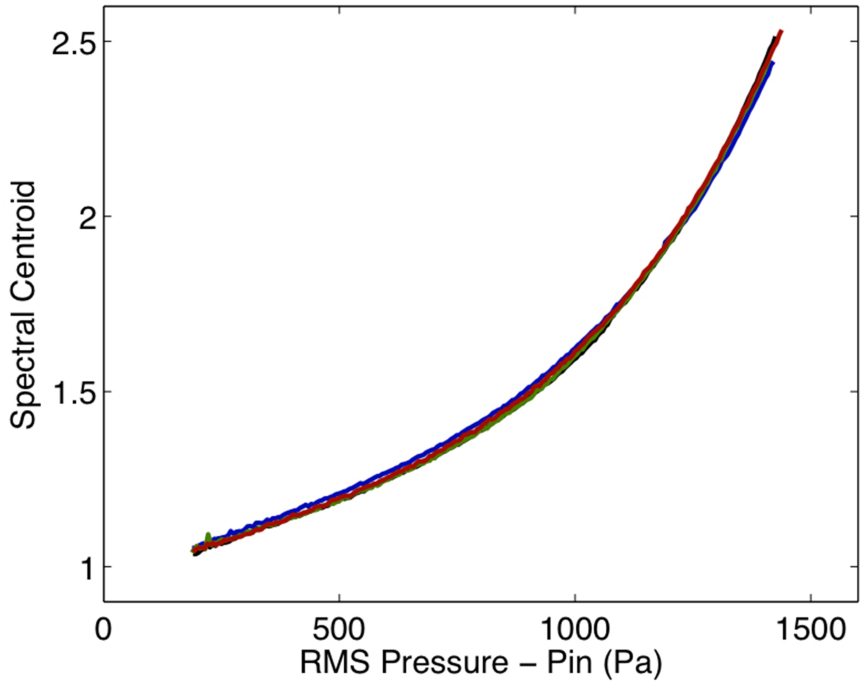


Figure 3.9: Brassiness curves showing the variation in spectral centroid with increasing pressure for four similar horns crooked in F: Uhlmann (GB.CAS.prowse, 1), Kretzschmann (GB.E.u, 531), Courtois (GB.E.u, 4668), and an anonymous horn (GB.E.u, 2888).

the tonal characteristics of these instruments should be so similar, but there is a possibility that there was greater standardisation in horn design concerning the more common pitch of F (their bore profiles are all quite similar); the spread in the range of brassy curves for instruments pitched in A is wider.

3.4.3 Modern and early horns

One of the most significant changes in the design of brass instruments over the past three hundred years has been the widening of the bore, and it is significant because this trend directly affected the timbre of brass instruments. There was a desire for the brass section to have a bigger sound to match the expansion of the orchestra in the nineteenth century. Musicians wanted to play louder but without the sound becoming excessively bright and brassy.

The graph in Figure 3.10 shows a relatively wide-bore modern double horn, a Conn 8D (GB.E.chick, 2007.3) (black curves), compared to a narrower-bore mid-eighteenth century horn by the maker Hofmaster (GB.E.u, 3296) (red curves). Up

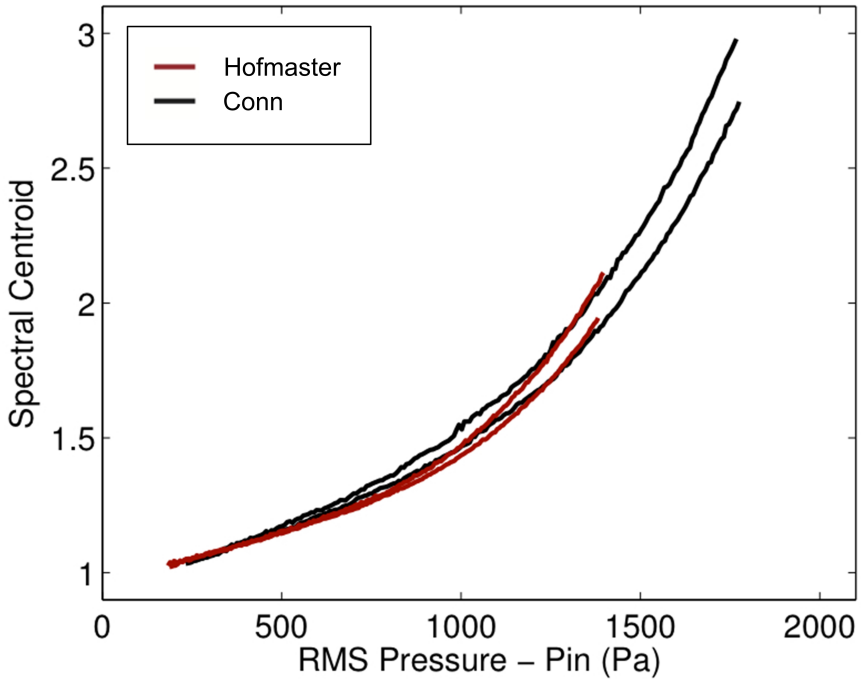


Figure 3.10: Brassiness curves showing the variation in spectral centroid with increasing pressure for two different horns crooked in D (upper curves) and F (lower curves). Conn (GB.E.chick, 2007.3) (black curves) and Hofmaster (GB.E.u, 3297) (red curves).

to about 1000 Pa, the modern instrument appears to have a slightly higher spectral centroid value across both F and D pitch lengths, than the Hofmaster horn. As the

input pressure increases above this value however, the timbre of the early horn, becomes enriched with upper harmonics more rapidly than the modern Conn.

It should be noted that the maximum input pressure for the early horn in these measurements reaches about 1400 Pa, but in reality a player is capable of input pressures in the region of 3000 Pa. If the curves corresponding to the Hofmaster horn in Figure 3.10 were to be extrapolated, it can perhaps be predicted that at higher dynamic levels than shown here, the Hofmaster horn would sound brassier than the modern double horn. Due to the difference in bore, it is also the case that, for a given input pressure, a wider bore horn will produce a greater total radiated sound power than an instrument with a narrower bore.

3.5 Conclusions

Exploration of brassiness characteristics in brass instruments is not only useful for identifying different types of instrument, but this research has shown that within the family of horns, it is also useful for exploring evolutionary trends. Preliminary results suggest that narrow-bore horns from the baroque and classical era tended to show greater brassiness potential than wider-bore modern instruments. It would be useful to explore this area further by expanding the dataset to include more modern horns. The characteristic timbre of each instrument was also retained when making comparisons with various crooks.

The difference in tonal characteristic of long crooks such as 14-ft D compared to short crooks such as 10-ft A was also clearly evident and supports the idea that nineteenth-century horn players were reluctant to give up the crooked horn in favour of valves, because they were worried about a loss in tonal variation. It would be interesting to explore this area further by measuring the brassiness potential of the very shortest (8-ft C alto) and longest (18-ft B$^{\flat}$ basso) crooks.

In the majority of cases, it was clear to see early on, at a relatively low dynamic level, how brassy the instrument would become in relation to other horns. In a few cases however, it was interesting to observe that at low to medium input pressures,

two horns might share very similar brassiness characteristics, but above a certain point the curves diverged significantly. Closer analysis with detailed measurements of the bore profiles are needed to explore this area further.

These measurements were all taken with the hand out of the bell, but of course the damping effect of the hand placed within the bell, greatly changes the tone quality of the radiated horn sound, and many of the instruments tested here were made to be played with hand technique in mind. It would therefore be interesting to explore the extent to which the hand in the bell changes the brassiness characteristics and acoustics of different horns. This is an area which will be explored in some detail in Chapter 4, revealing a link between the chronology of early horns, and the effect of the hand in the bell on intonation and security in the high register.

Chapter 4

Technique

The ambiguity of evidence surrounding the technique used by horn players in the eighteenth century is explored from an acoustic angle in the following chapter. The introduction (4.1) provides some brief historical background to the topic, then goes on to explain the main analytical tool in this approach: acoustic impedance. The chapter is then split into two main parts in order to examine embouchure technique (4.2) and hand technique (4.3) separately. The last section (4.4) draws together analysis from both parts.

4.1 Introduction

There is great uncertainty concerning the exact methods by which the horn was played in the eighteenth century. It was during this period that players started experimenting with hand technique in earnest, but precisely when this new technique took hold, and in which regions, is largely unknown. The discovery that placing the hand within the bell of the instrument allowed greater control over the pitch of the notes, opened up a whole new range of musical possibilities for horn players, and also for composers writing for the instrument.

Prior to the advent of hand technique, the only way of fine tuning the natural notes of a brass instrument was for the horn player to use a method often referred

to by players as 'lipping'. The technique involves muscular manipulation of the embouchure and was also adopted by trumpeters around this time [Tarr, 1988, p.122-123]. The use of the word 'lipping' is perhaps slightly misleading because the technique actually involves the manipulation of the whole of the mouth and embouchure to change the pitch of the note; the lips, the tongue, the oral cavity, and mouthpiece pressure may all be brought into play when lipping, and different musicians achieve this effect in different ways. Another term used to describe the technique is 'pitch bending' but since it is not immediately apparent from this phrase whether pitch bending refers to embouchure or hand manipulation, the term 'lipping' will predominantly be used throughout this thesis.

Unlike the early horn, the bell of the early natural trumpet is not so conveniently located for easy access with the hand, and so the only option for the trumpeter would have been to employ the lipping technique. Controlling the pitch of a note with the embouchure alone is more limited in its scope for pitch flexibility than with the hand, and so for horn players it was the latter technique that prevailed.

Eighteenth-century composers writing for the horn would most likely have had the idiosyncrasies and capabilities of one or other technique in mind, depending on the practice at the time, but doubt remains as to when exactly hand technique became established in different regions of Europe. As a result, the question of whether or not it is authentic to play with the hand in the bell when performing a particular piece of music is a pressing issue today for those musicians involved in historically informed performances.

Much of the surviving archival documentation and iconography (e.g. methods, tutors, manuscripts, paintings, etc.) have been scrutinised countless times, yet the topic remains controversial, and so in this chapter, an alternative approach is proposed; applying techniques of acoustic analysis on extant instruments in the hope that further light will be shed on the problem. Original early horns provide a wealth of untapped information, not immediately apparent upon initial observation or when examined in isolation.

4.1.1 Challenges of early horn technique

The natural horn is capable of producing a number of notes whose resonant frequencies are approximate to a harmonic series. Understanding and becoming completely familiar with this series is essential for the natural horn player; not only was music of the time based on these notes, but the series is also fundamental to the acoustics of the instrument. The notes in the series are referred to as the natural resonances, or resonant modes of the air column of the instrument, and they can be measured objectively with acoustic equipment in order to generate an input impedance curve (further discussion and examples of such curves can be found in Sections 4.1.3 and 4.1.4). The length of the horn determines the key of the approximate harmonic series and explains the need for the horn player to change crooks to play in different keys.

On a horn crooked in E♭ or D, it is quite possible to play up to the twenty-fourth resonant mode,* but playing in the extremes of the high register is physically demanding. Also, because the pitch interval between the resonant modes gets smaller with increasing pitch, it is much easier to miss the target note (i.e. 'split' a note) and land on the wrong resonance in the high register of the horn. On the other hand, this register was very attractive to eighteenth-century composers, because the greater variety of notes in this region meant there was more potential for the development of melodic lines. As a result, much of the music from the baroque period features extremely high horn writing which musicians of the day were apparently capable of playing.

This skill has largely fallen out of practice in the intervening years, and brass players today attempt to overcome the problem by employing shorter instruments which provide more security in the high register but at the expense of tone quality. More recently however, there has been an increasing interest in reviving the skill of high brass playing on the longer lengths of instrument originally intended, and this has led to an awareness that some instruments, particularly early examples, are more suited to high register playing than those of a later date. The placement of the

*Examples of music where these high notes can be found include: Peter Fux (1753-1831), Concerto in E♭; Josef Fala (1748-1811), Concerto in E♭; and Jan Dismas Zelenka, (1679-1745) *Capriccio I* in D.

hand within the bell of the horn also effects the response and feeling of security in the high register. Acoustic measuring techniques can be useful for observing these differences, without the need to play the instrument.

Some of the resonant modes on a natural brass instrument do not fit comfortably within western musical tempered scale tunings; the seventh, eleventh, and thirteenth in particular can be quite 'out of tune', at least to our modern ears. On the assumption that musicians would have wanted to alter these wayward notes (at least to some extent), horn players would most likely have used either the lipping technique or hand technique, or a combination of both for this purpose. Using the embouchure to manipulate the pitch of notes on a brass instrument is a technique generally thought to have preceded the use of the hand in the bell. Similar to the case with high register playing, some horns are more suited to hand technique or embouchure manipulation than others, and analysis of acoustic measurements can also be used to explore these differences.

4.1.2 Challenges in assessing playing characteristics

It could be argued that experienced musicians are best placed to assess the playing characteristics of the horn, but for reasons of preservation, this is often not an option when studying historic instruments. Another issue concerns the subjectivity of player tests as a result of individual preference. For this reason, consistency in the quality of results is not always achievable. On the other hand, musicians are extremely sensitive at detecting subtle changes in the design of an instrument or anomalies in the manufacturing process, and for this reason player tests often form a very good starting point for acoustic research. The initial research into lipping technique described in Section 4.2 is based on player tests.

Acoustic tests such as the measurement of the input impedance of an instrument offer an alternative, more objective approach. This method also has a significant advantage over player tests because it is non invasive and requires little contact with the horns. Brass instruments are perishable and owners of collections are becoming increasingly sensitive to issues of excessive handling and contact.

It is already the case that many eighteenth-century horns are no longer in playing condition due to large dents, leaks, or cracks in the metal. A thick layer of dust inside the tubing or a trapped foreign object could alter the acoustics of an instrument, so in the case of instruments that have already experienced significant wear and tear, and are no longer in playing condition, extrapolated measurements of their bore profiles may be used as the input to computational models in order to predict the acoustic impedance of the instrument (discussed further in Section 6.2.2). In the following acoustic experiments, only instruments which appear to be in reasonable playing condition have been included.

4.1.3 Measuring acoustic impedance

The measurement of acoustic impedance provides an objective and unique indication of the response of an instrument. At any given frequency it can provide information about the strength of the sound pressure in the air column of the instrument, thus predicting the natural modes of resonance the instrument is capable of producing. Acoustic impedance is usually given the symbol Z and can be defined simply as the ratio of acoustic pressure fluctuation to acoustic volume velocity:

$$Z = p/U, \tag{4.1}$$

where p is the pressure amplitude, and U is the volume velocity, both at a given frequency.

In the following series of experiments described in this chapter, the equipment used to measure the acoustic input impedance of the various horns is the commercially available Brass Instrument Analysis System (BIAS). In the BIAS impedance head there are two small microphones positioned at either end of a high-impedance capillary, over which the mouthpiece is positioned. These microphones measure the sound pressure at both points simultaneously. A loudspeaker, also enclosed in the measuring head, emits a frequency sweep referred to as a chirp. The BIAS software is programmed to convert the information picked up by the microphones, corresponding to pressure fluctuation and alternating airflow, into data which can then be displayed as a graph showing the input impedance curve.

It can be calibrated by measuring the impedance of two very short, closed tubes, of known volume. These act as reference volumes and the difference between the theoretical input impedance for both calibration volumes, compared to their respective measurements, can then be used in the calibration calculation.

Measuring the acoustic impedance of an instrument is a useful starting point when considering its playing properties. The graph in Figure 4.1 shows an example of an impedance curve for a typical mid-nineteenth century natural horn by the maker Andreas Barth (A.KR.sk, Piz.003). It was measured without the hand in the bell and using a PHC 22 mouthpiece (more information about the mouthpieces used in these experiments can be found in Sections 4.2.1 and 4.3.1). Each peak on the graph corresponds to a note or resonant mode on the horn and provides information about its pitch and strength. The peaks are close to being evenly spaced in terms of frequency, as one would expect given that the modes are very close to forming a harmonic series. The overall shape, or envelope, of the impedance curve is strong in the low to middle registers, getting weaker as the pitch increases, with no significant peaks after about mode sixteen; this broadly corresponds to the response the musician might experience when playing the horn without the hand in the bell.

4.1.4 Interpreting acoustic impedance

The envelope of an impedance curve varies from instrument to instrument depending on the shape of the respective bore profile. Figure 4.2, shows a very different impedance curve to that in Figure 4.1. This measurement was taken on a typical late-eighteenth century horn by the maker William Shaw (A.KR.sk, 216), again measured without the hand in the bell.

A possible reason for the difference between these two impedance curves, is that the two horns use different crooking systems. As a result, their bore profiles vary significantly during the first metre of tubing, as measured from the mouthpiece receiver, see Figure 4.3. There is a much more rapid expansion in the initial section of tubing on the horn made by Shaw (bold line) than on that by Barth (A.KR.sk,

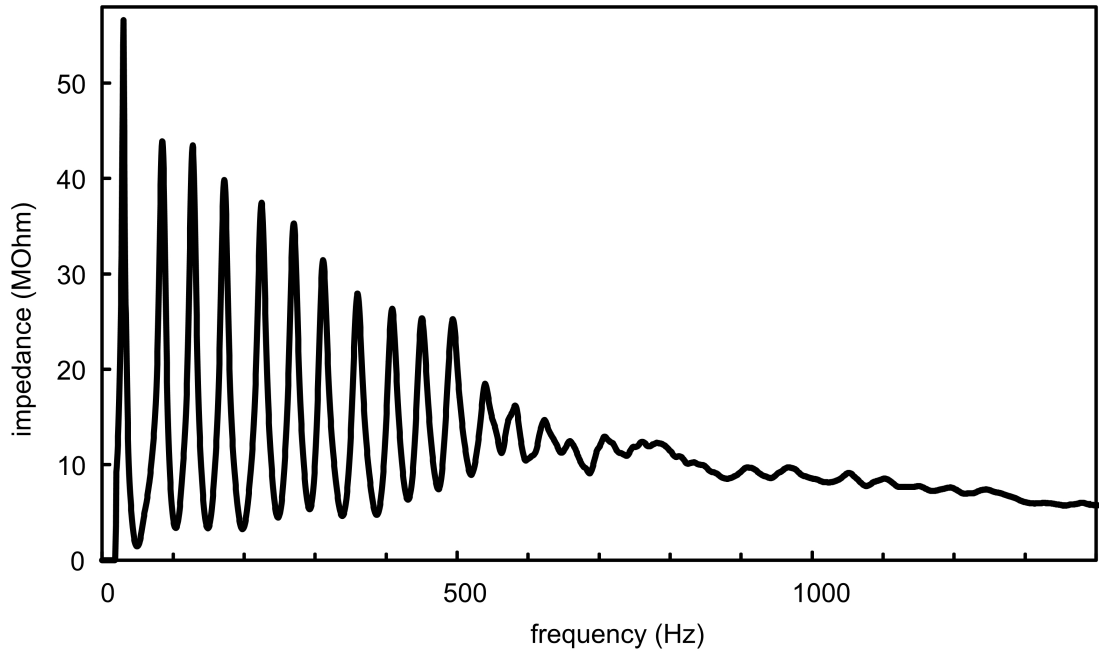


Figure 4.1: Input impedance curve measured (without the hand in the bell) on a horn by maker Andreas Barth, from the mid-nineteenth century (A.KR.sk, Piz.003). This horn employs a terminal-crooking system.

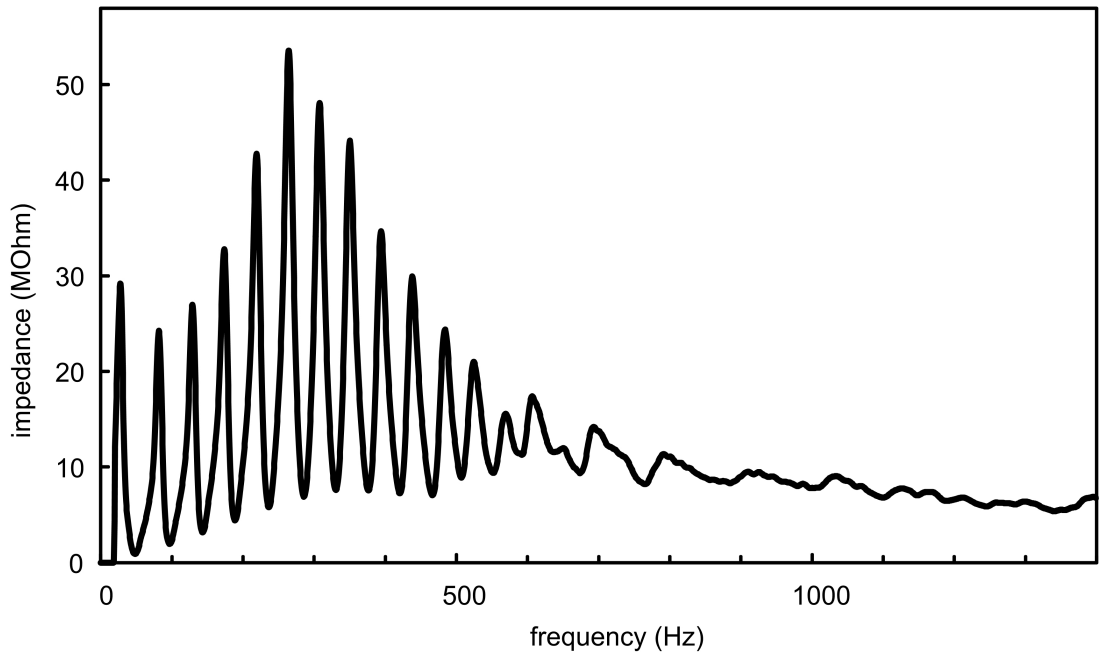


Figure 4.2: Input impedance curve measured (without the hand in the bell) on a horn by William Shaw, from the late eighteenth century (A.KR,sk, 216). This horn employs a master-crook-and-coupler system.

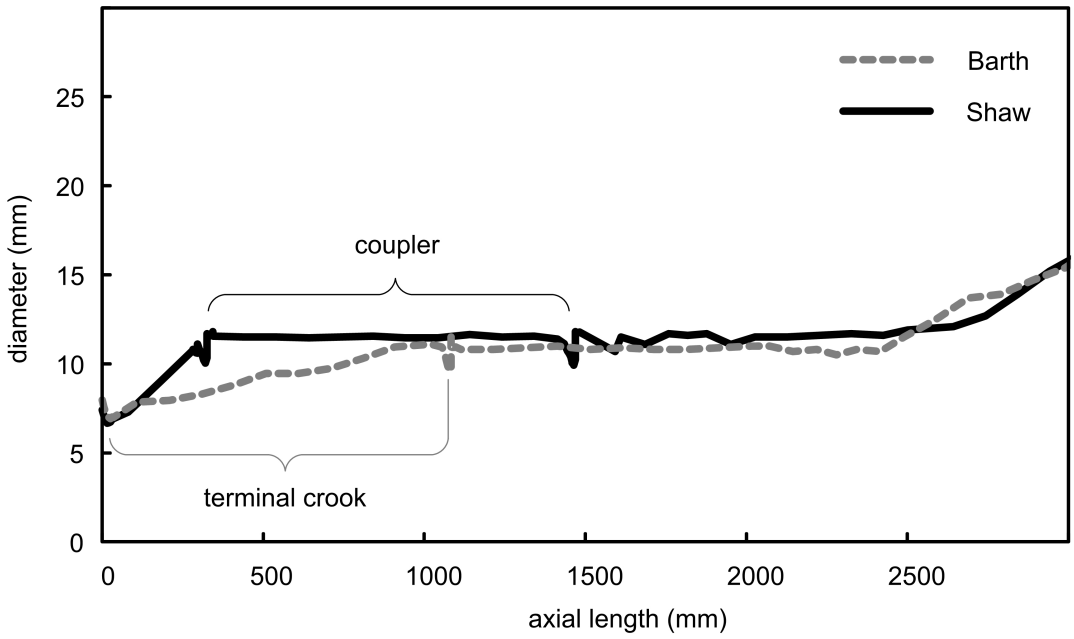


Figure 4.3: Bore profile comparison showing the difference between two types of crooking system; the terminal-crooking system on a horn by Barth (A.KR.sk, Piz.003) and a master-crook-and-coupler system on a horn by Shaw (A.KR,sk, 216).

Piz.003) (dashed line). This can be explained by the fact that a crook-and-coupler system is used on the Shaw horn, i.e. both a master crook and couplers are employed to achieve the desired pitch. The cylindrical coupler section is annotated on the graph in Figure 4.3 and the expanding section preceding this is the short master crook. The horn by Barth on the other hand, requires only one gradually expanding terminal crook in order to achieve the same overall pitch (also annotated on the graph). Definitions of the various types of crook can be found in the glossary at the beginning of this thesis.

To check that it was indeed the different crooking systems which were influencing the shape of the impedance curves, a computational model was used to predict the acoustics of the horns (without the hand in the bell) based on bore profile measurements (see Section 6.2.2 for more information about the model). Firstly the impedance curve of the Barth horn was predicted in order to see how closely this compared to the original impedance measurement in Figure 4.1. The result is very similar and a comparison is shown in Figure 4.4. Then the initial section of the Barth bore profile was altered, replacing the terminal-crook measurements

with the crook-and-coupler measurements from the horn by Shaw. Essentially, the new hybrid bore profile is made up of the Barth corpus with the Shaw crooking system. The modelled impedance for this hybrid instrument is shown in Figure 4.5, compared to the original measurement on the Shaw horn from Figure 4.2. From these graphs it can be seen that the shape of the impedance curve does appear to be strongly influenced by the different crooking systems in use.

The seven various terminal crooks, for the horn by Barth, allowing it to be played in all the most important keys, can be seen in the photo on the left in Figure 4.6. On the right is a photo of the horn by Shaw with one master crook and a selection of couplers inserted into the corpus of the instrument. The master-crook-and-coupler system is most commonly associated with horns from England, and its advantage was that the horn player could carry around fewer and shorter sections of tubing in order to play in all the different keys required, because couplers can be used in combination. The terminal-crooking system however, requires a separate crook for each key, but its virtue is greater stability and ergonomic comfort near the mouthpipe, and the possibility of a more gradual taper in the mouthpipe.

It is interesting, but perhaps not surprising, that the different crooking systems have a significant influence on the acoustics of the horn; small changes in the region of the mouthpipe (which is part of the very narrowest section of a brass instrument) are crucial to the behaviour and the acoustics of the instrument. From the measurements shown in the previous graphs (Figures 4.1 and 4.2) it can be predicted that the response in the very low register of the horn by Shaw would be quite unstable and weak at quiet dynamic levels when compared to that by Barth. Similar patterns concerning the shape of impedance curves for each type of crooking system were observed among the other horns included in this study.

It should be noted however, that although an impedance peak might display a relatively low amplitude, with increasing loudness, higher harmonics would be excited, providing positive reinforcement from the stronger upper resonances, and the tone would become more stable. This is because the graphs showing the input impedance curves describe only the linear aspect of the behaviour of a brass instrument, and this linear effect is closest to describing how an instrument might behave at the very quietest of dynamic levels. Increasing dynamic level leads to

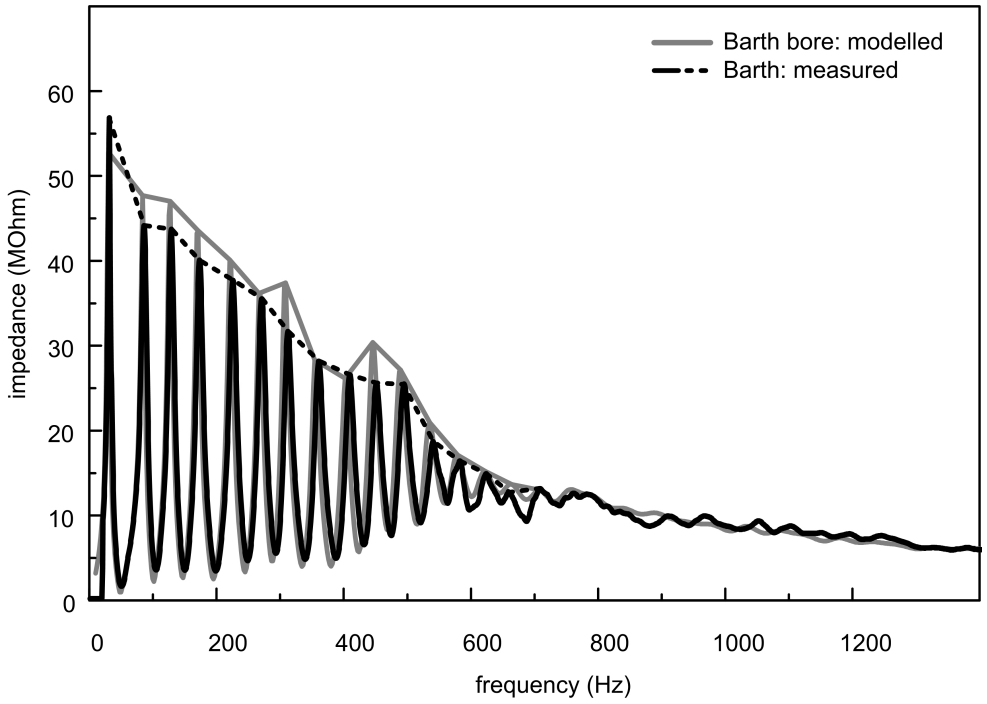


Figure 4.4: Comparison between the modelled input impedance based on bore profile measurements taken from a horn by Barth which employs a terminal-crooking system (A.KR.sk, Piz.003), and the previous measurements shown in Figure 4.1.

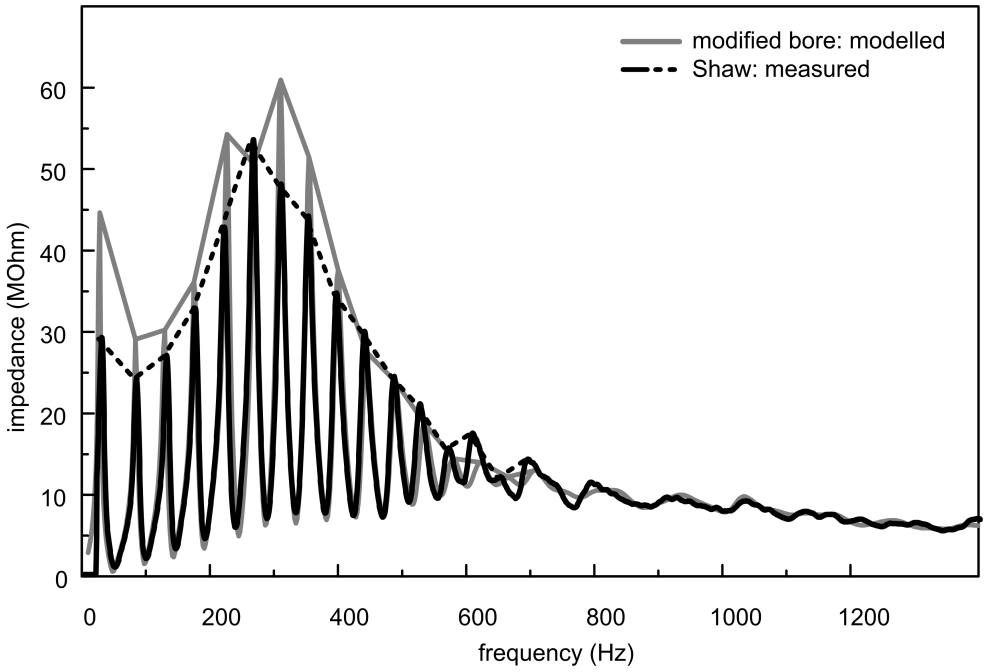


Figure 4.5: Comparison between the modelled input impedance based on a horn by Barth where the terminal-crook measurements have been replaced with crook-and-coupler measurements, and the previous measurements shown in Figure 4.2 from the horn by Shaw.

Figure 4.6: The seven terminal crooks (left) are from a horn by Barth (A.KR.sk, Piz.003) with two additional couplers in the middle; only one master crook and four additional couplers (right) are from a horn by Shaw (A.KR,sk, 216).

an increase in non-linear behaviour. Previously (in Section 3.2) non-linearity was described in relation to changes of pressure in the air column of the instrument, but it is also an effect created by the non-linear behaviour of the lip valve.

From a practical point of view, these different crooking systems are likely to have had some effect on the ease with which the hand could be manipulated within the bell of the horn (a full discussion on this appears in Section 5.4.3 concerning design and ergonomics), and possibly also the ability to employ lipping technique too, due to issues of stability of the mouthpiece on the lips when the hand is located further from the mouth of the musician. But the main purpose of the preceding discussion was to show that the different bore profile shapes, resulting from the various horn designs, clearly have an impact on the acoustics of the instrument, which can be observed in the contrasting acoustic impedance curves. The rest of this chapter will look at what other information can be extracted from these impedance curves in order to gain a greater understanding of the acoustic effect of the hand in the bell and the ease with which a player can lip certain notes.

4.2 Embouchure

Arguably the most fundamental aspect of the acoustical design of a brass instrument is the creation of a bore profile designed to produce a set of musically useful resonances, which are close to being harmonically related. The harmonicity of this series is important as it allows for a strong coupling between the resonances of the air column within the instrument, helping to support the oscillation of the lips, a key function of the player's embouchure. This interaction is also known as a cooperative regime of oscillation [Benade, 1973]. Although the internal shape of the instrument determines the frequencies at which the lips will most readily vibrate, the player still has the ability to exert some influence on the finer tuning of these resonances by employing lipping technique.

Horns and trumpets from the eighteenth century do not have valves (the invention of which extended the range of notes available to the player), and so seventeenth- and eighteenth-century composers were restricted to using predominantly the natural resonances of the instrument. As mentioned previously (in Section 4.1), most of the resonances correspond to the notes of a tempered scale but the seventh, eleventh and thirteenth do not fit comfortably within these tuning systems. Wayward pitches such as these were most likely problematic for musicians of the day, and they remain an issue for modern brass players interested in performing on natural instruments. What technique was applied to which historic instruments in order to fine tune certain notes?

Baroque composers do not seem to have made a particular effort to avoid these problematic pitches in their horn and trumpet writing. The written F♮ and F♯, for example, are two notes frequently used by composers around this time, and yet both notes share the same natural resonance, the eleventh, which falls somewhere in between the two pitches. Players would have been required to distinguish between these two notes and therefore would have had to 'bend' the pitch of the eleventh resonance up or down accordingly. The short excerpt in Figure 4.7 shows the second horn part (middle line) for a piece of music written by the early eighteenth-century composer, Johann David Heinichen, in which both F♮ (highlighted in blue) and F♯ (highlighted in red) are required to be played by the musi-

Figure 4.7: A short excerpt taken from a Concerto in F (S.233) by Johann David Heinichen (1683-1729), showing that the second horn player is required to play both an F♮ and an F♯.

cian. If these had been written instead as merely passing notes, the importance of distinguishing between the F♮ and the F♯ would perhaps seem less important, but instances of both notes fall on the beat and are essential to the changing harmonies of the musical passage at that moment.

There has been some discussion amongst players and scholars, that some early original brass instruments may be better suited to the demands of eighteenth-century repertoire than their modern counterparts, particularly with regard to lipping potential. This is arguably because the resonant modes on these early horns and trumpets are not as harmonically aligned as on either modern instruments, or even copies of early eighteenth-century instruments [Fromme, 1972; Smithers *et al.*, 1986], and that this in some way aids the application of early performance techniques.

A related study exploring the acoustical properties of different trumpet mouthpieces, Poirson *et al.* [2005] has suggested that slight inharmonicity might in fact be a desirable quality in any brass instrument. From the point of view of pitch bending, misalignment in the series of resonant modes would result in weaker support from higher resonances and could thus, in theory, provide the player with

greater flexibility of pitch, i.e. greater lipping potential. It is an interesting theory, and the rest of this section investigates some of the features of horn acoustics which might indicate the potential of an instrument to respond to pitch manipulation.

4.2.1 Methods of analysis

It is not obvious what makes one instrument more amenable to pitch bending with the embouchure than another, and so the first step in this investigation was to find out which instruments players found easiest to apply the lipping technique on, and whether the type of mouthpiece used has any influence on this aspect of technique.

Initial analysis involved carrying out a series of playing tests on ten different horns, including five early orchestral horns from the Edinburgh University Collection of Historic Musical Instruments by makers Hofmaster (GB.E.u, 3296), Kretzschmann (GB.E.u, 531), Sandbach (GB.E.u, 203), Winkings (GB.E.u, 2492) and one anonymous horn (GB.E.u, 2888). Figure 4.8 shows a photograph of one of these early instruments, a horn from the mid-eighteenth century, made in England by the maker Nicholas Winkings (GB.E.u, 2492). The date of manufacture for the horns tested, range from the mid-eighteenth to the early nineteenth century. A modern copy of an early orchestral horn was also included in the dataset (GB.E.chick, 2008.1). This was the instrument used for the playing tests comparing various mouthpiece designs (further details on all horns included in these experiments can be found in Appendix A alongside references to the relevant sections where the instruments are discussed).

For the purpose of this investigation, all horns were crooked in D, a common key for horn players of the eighteenth century to play in,* and the tests were carried out without the hand in the bell in order to limit potential variables. The effect of the hand in the bell on the acoustics of the horn is explored fully in Section 4.3.

*A horn crooked in D has a tube length of approximately 4.42 m, corresponding to a nominal pitch of D_1

Figure 4.8: Photograph of a horn by the London maker Nicholas Winkings, from the mid-eighteenth century (GB.E.u, 2492).

The mouthpiece forms part of the very start of the bore profile of a brass instrument, and players are particularly sensitive to changes in this region. For this reason, a set of playing tests was first carried out where the instrument was kept the same but three different commercially available mouthpieces by Paxman-Halstead-Chidell (PHC) were substituted. Figure 4.9 shows detailed bore profiles for each mouthpiece. Measurements of mouthpiece and horn bore profiles were taken using equipment such as callipers and measuring rods (a full description of bore measuring techniques can be found in Section 6.2).

The profile of the mouthpiece with the deepest cup (PHC 35) shown in blue in Figure 4.9, is closest to the funnel-shaped profile of many early horn mouthpieces, with barely a throat to distinguish between the cup and the backbore. The intermediate of these three mouthpiece designs (PHC 23A) shown in green, is a model commonly used by players today, and the red mouthpiece profile (PHC 20) shows the shallowest of the three models, displaying quite a pronounced cup shape. This

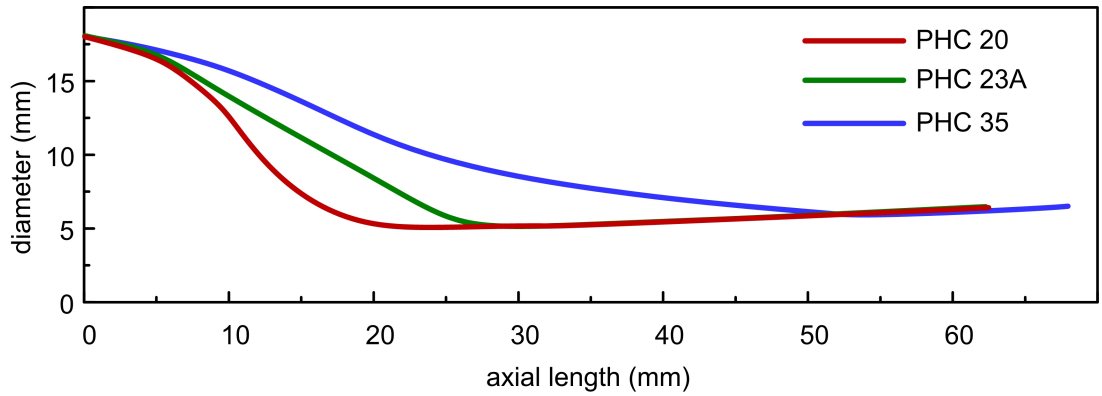


Figure 4.9: Bore profile comparison of the internal shape of three different horn mouthpieces: PHC 20 (red) shallow cup; PHC 23A (green) medium cup; PHC 35 (blue) deep cup.

design is more similar to that of a typical trumpet mouthpiece and is increasingly used by modern horn players to help with playing in the high register.

Each player was invited to use her or his own mouthpiece rim which could be transferred between the three mouthpieces during the playing tests. The advantage of this is that the rim has no significant effect on the acoustics of the instrument, but allows the player some degree of familiarity between tests.

The photograph in Figure 4.10 shows the experimental setup for recording the playing tests. During the lipping experiments, the hand was not placed within the bell of the horn. The radiated sound from the bell of the instrument was measured using a Bruël and Kjær 4192 pressure-field microphone, located one bell diameter from the plane of the bell of the instrument, on axis. In addition to the radiated sound, the mouthpiece pressure was recorded using a 106B PCB Piezotronics dynamic pressure transducer located near the throat of specially modified mouthpieces as shown in Figure 4.11. The signals from both transducers were sampled at 44.1 kHz.

A total of five experienced horn players provided the playing samples for the experiments. They were all given a familiarisation period with each instrument or mouthpiece before starting the recording process. The same set of playing tests was applied to both horn and mouthpiece investigations.

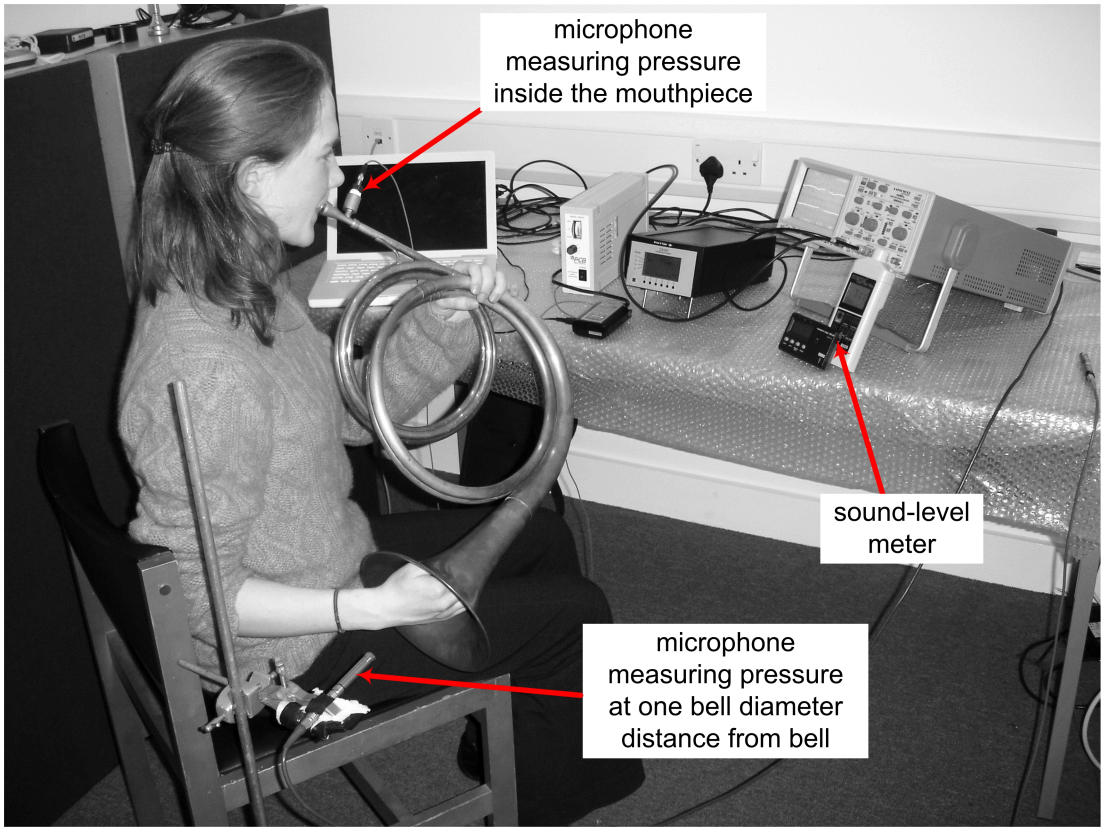


Figure 4.10: Experimental set up, showing the positions of the microphones and sound-level meter.

Firstly, players were asked to bend the pitch of the fourth resonance downward as far as they could until the note dropped to the third resonance below.* Typically the sound samples lasted for about two to three seconds. The test was to be played at a strong dynamic level, approximately *forte*, and was repeated at least four times. To assist the players with keeping the sound at a constant dynamic level over the duration of the pitch bend, they were provided with a sound-level meter (set to A-weighting). The players then carried out the same set of tests but this time attempted to bend the pitch of the resonance upwards as far as it would go until the note jumped to the higher, fifth resonance.† The players were asked to make no attempt to aim for a specific pitch, only to test the extremes of the flexibility of the pitch on the particular resonance. The lipping potential of the eleventh resonance

*The fourth resonance for a horn crooked in D corresponds to a written C_4 (or at concert pitch, D_3) and the third resonance to a written G_3 (or at concert pitch, A_2).

†The fifth resonance for a horn crooked in D corresponds to a written E_4 (or at concert pitch, $F_3^\sharp$).

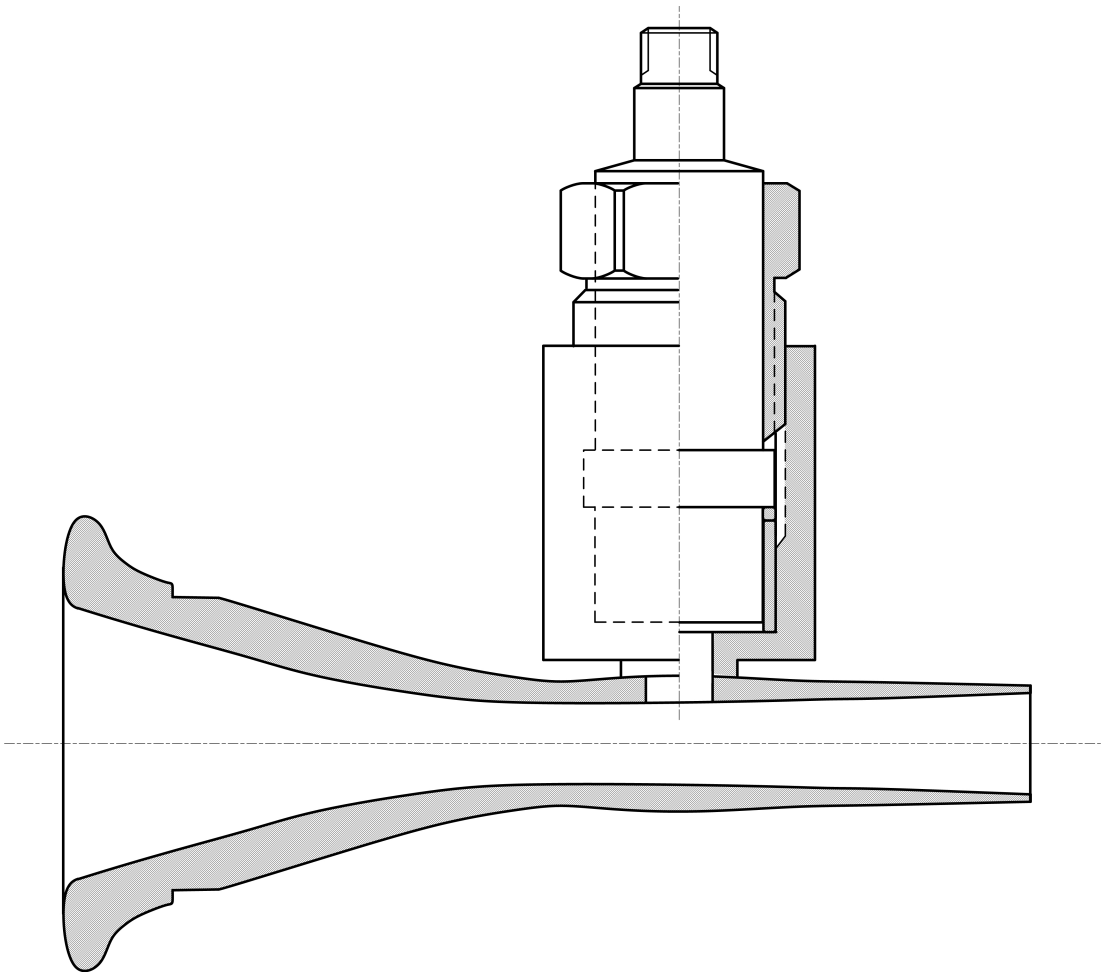


Figure 4.11: Diagram of a horn mouthpiece with a specially made fitting for a microphone.

was explored in the same way for all horns and mouthpieces.*

The reason for testing the pitch bending capability of the fourth resonance is because it is relatively low in the playing range of the horn and therefore is easier to manipulate with the embouchure. The eleventh resonance was chosen because, although it is higher in the series and more difficult to lip, it is a particularly problematic pitch as mentioned earlier, which typically lies somewhere in between a written $F^{\natural}$ and $F^{\sharp}$. This resonance would certainly have been subjected to some

*The tenth, eleventh and twelfth resonances for a horn crooked in D correspond to written E_5, F_5 and G_5, respectively (or at concert pitch, $F^{\sharp}_4$, G_4 and A_4). However the eleventh resonance, as noted earlier, does not generally agree exactly with this pitch.

form of pitch manipulation as composers include both these notes in their compositions (see Figure. 4.7).

After having conducted the playing tests, the initial analysis of the recordings was carried out using the pitch detection software 'Praat' [Boersma, 2002], a program originally developed for speech analysis, but found to work well for instrument analysis also. Further analysis was carried out by looking at the acoustic input impedance curves for each horn and mouthpiece combination. A detailed description of this method of analysis is found previously in Section 4.1.3. The intensity and the spectral content from a selection of the sound samples was also analysed.

4.2.2 Mouthpiece results

The shape of the horn mouthpiece has changed slightly over the past few hundred years; the main difference concerns the narrowing of the throat in more recent times. Many early horn mouthpieces have no distinct throat and the design is much more funnel-shaped than on modern examples. The three mouthpieces used in this investigation are all of modern manufacture but they were chosen because their bore profiles demonstrate the narrowing of the throat very clearly, as seen previously in Figure 4.9.

During the experiments, most of the players commented that the feedback, or response, varied greatly between the shallowest and deepest mouthpieces, but when the sound clips were analysed using the Praat software, there was no discernible difference concerning the extent of pitch manipulation from within any one set of player results. Figures 4.12 and 4.13 show typical downward pitch bends from the eleventh resonance to the tenth, for both the PHC 20 (shallow) and PHC 35 (deep) mouthpieces.

The two sound samples were taken from the same set of player tests and in both of these examples the pitch varies by about thirty cents. Concerning the recordings in general, small differences were observed regarding the extent of pitch manipulation between players but no individual person showed a strong preference for

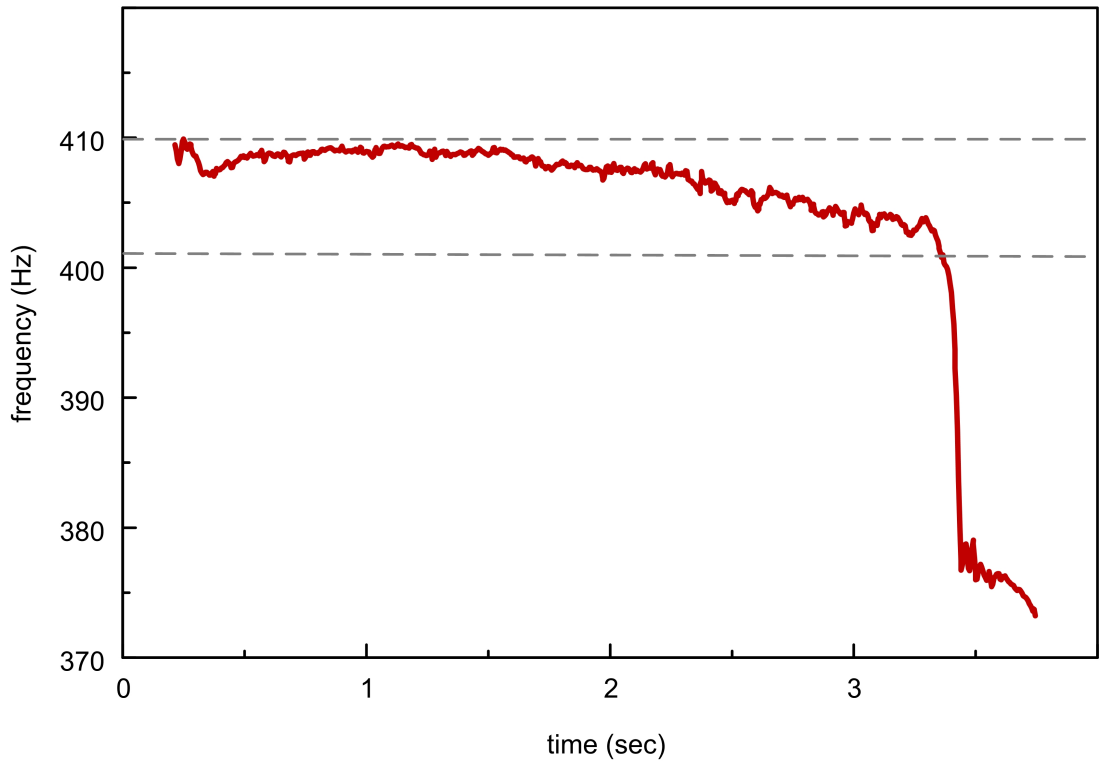


Figure 4.12: Graph showing the change in pitch as the eleventh resonance is lipped downwards until it drops to the tenth resonance, played on a shallow-cup mouthpiece, PHC 20. Dashed lines indicate approximate maximum and minimum frequencies on the eleventh resonance.

being able to apply lipping technique more easily on any one particular mouthpiece (see Appendix C for additional lipping data).

The feedback from the players about the varying response from the instrument when changing between mouthpieces prompted an investigation into the effect of different designs of mouthpiece on the acoustic impedance of the horn; the results can be seen in Figure 4.14. The impedance curve relating to the shallowest mouthpiece (PHC 20) is shown in red and the deepest mouthpiece (PHC 35) in blue. The intermediate cup (PHC 23A) impedance curve (in green) falls in between these two extremes, which is to be expected.

On initial observation, these three curves look very different; the amplitudes of the resonant peaks vary significantly above about 300 Hz (above a written A_4 for horn in F) and the individual shapes of the three impedance envelopes are quite distinct.

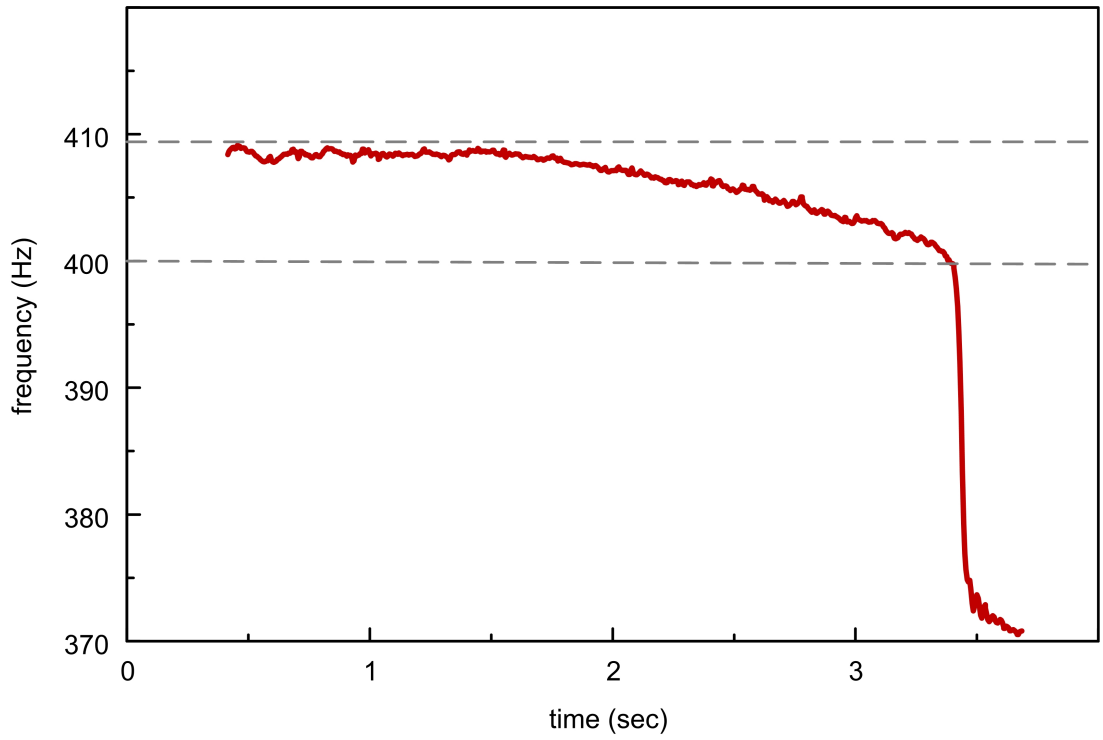


Figure 4.13: Graph showing the change in pitch as the eleventh resonance is lipped downwards until it drops to the tenth resonance, played on a deep-cup mouthpiece, PHC 35. Dashed lines indicate approximate maximum and minimum frequencies on the eleventh resonance.

There is one important similarity however: the pitches of the resonant modes and therefore the harmonicity of each impedance curve is almost identical, particularly in the mid range. Greatest pitch variation occurs on the second resonant mode where the peak maximum for the shallow cup measurement (PHC 20) is about sixteen cents sharper than that of the deep cup (PHC 35), but in the region of the mouthpiece resonances, near modes seventeen and eighteen (at about 650 Hz), the difference in pitch is less than one cent.*

The similarity of harmonicity between the three impedance curves, comparing the effect of different mouthpieces on the resonances of the horn, is worth noting because it may help to explain why the response of the instrument varied (as felt by the players), but the ability to manipulate the pitch with the embouchure did

*Note: a few Hz variation in the frequency of a low register resonance results in a much greater pitch change than the same frequency change occurring in the high register.

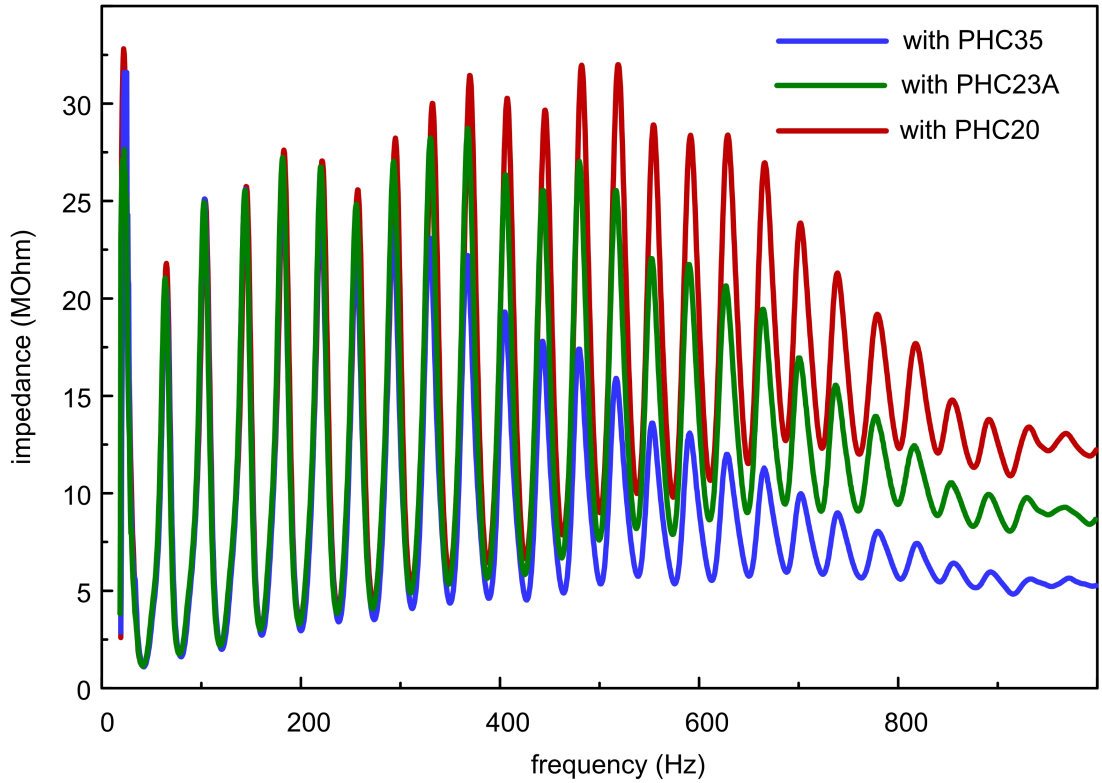


Figure 4.14: Input impedance curve comparison (without the hand in the bell) of three different models of mouthpiece by Paxman-Halstead-Chidell: deep cup PHC 35 (blue), medium cup PHC 23A (green) and shallow cup PHC 20 (red).

not. This idea is explored further in the Section 4.2.3 in which the harmonicity and the strength of certain resonances are shown to have a link with the ability to apply the lipping technique on certain horns.

The clear differences felt by the players might also be explained by the fact that these tests explored the extremes of flexibility, not the ease of flexibility. Attempting to quantify how easy a pitch is to manipulate is a different and more subjective task than taking a measurement of a change in pitch.

4.2.3 Horn results

Having first studied whether mouthpiece shape influences the ability of the player to manipulate the pitch with their embouchure (Section 4.2.2), and discovering

a negligible result, the next stage was to explore whether some horns are more suited to this aspect of early brass playing technique than others, and if so, to find out why. The following results reveal a subtle but measurable variation with regard to the lipping potential of specific notes on certain instruments.

Players found that a horn by the maker Hofmaster (GB.E.u, 3296) was relatively amenable to pitch bending on the eleventh mode (Figure 4.15) whereas an instrument by the maker Sandbach (GB.E.u, 203) proved to be less flexible on this resonance (Figure 4.16). Further data from these experiments can be found in Appendix C. Note that these two instruments are from different time periods and therefore have slightly differing nominal values of concert pitch; the Hofmaster horn is from the mid-eighteenth century whereas the instrument by Sandbach is from the early nineteenth century.

The graphs in Figures 4.15 and 4.16 display typical sound clips from one player, on each of these instruments; downward pitch contours can be seen showing the player moving away from the eleventh mode of resonance and dropping to the tenth mode near the end of the clip. On average, across all player tests, the pitch of the Hofmaster horn was found to drop by about eighty cents on this resonance, whereas the pitch of the Sandbach horn dropped by only about fifty-five cents (see Appendix C).

Not only was the instrument by Hofmaster found to be more flexible when bending the pitch downwards from the eleventh resonance, but it was also capable of being lipped more easily upwards from this resonance too. The graphs in Figures 4.17 and 4.18 show an equivalent comparison to the downwards pitch bend between the Hofmaster and Sandbach horns but for un upward pitch bend from the eleventh to the twelfth mode. Player feedback about the two instruments supports these findings; it was generally reported that the pitch of the eleventh resonance on the Hofmaster horn felt easier to manipulate than on any of the other instruments.

Having discovered a discernible difference between the pitch bending capabilities of two horns, the difficulty comes in trying to understand why the instruments respond in the way they do. For questions such as this concerning the response of

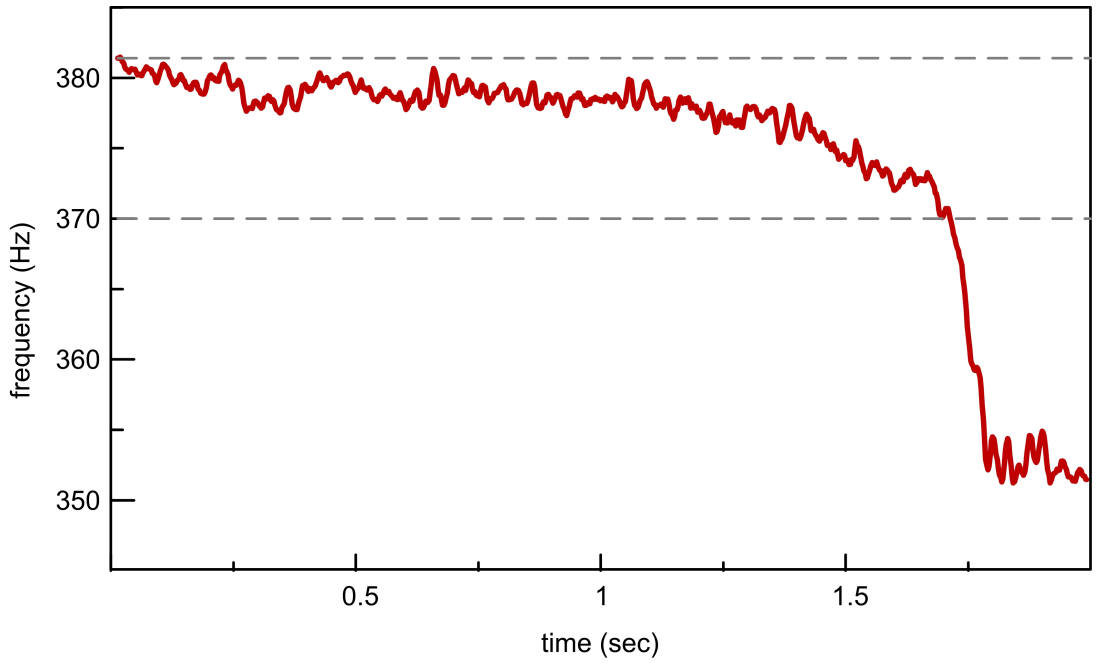


Figure 4.15: Graph showing the change in pitch as the eleventh resonance is lipped downwards until it drops to the tenth resonance, played on a horn by the maker Hofmaster (GB.E.u, 3296). Dashed lines indicate approximate maximum and minimum frequencies on the eleventh resonance.

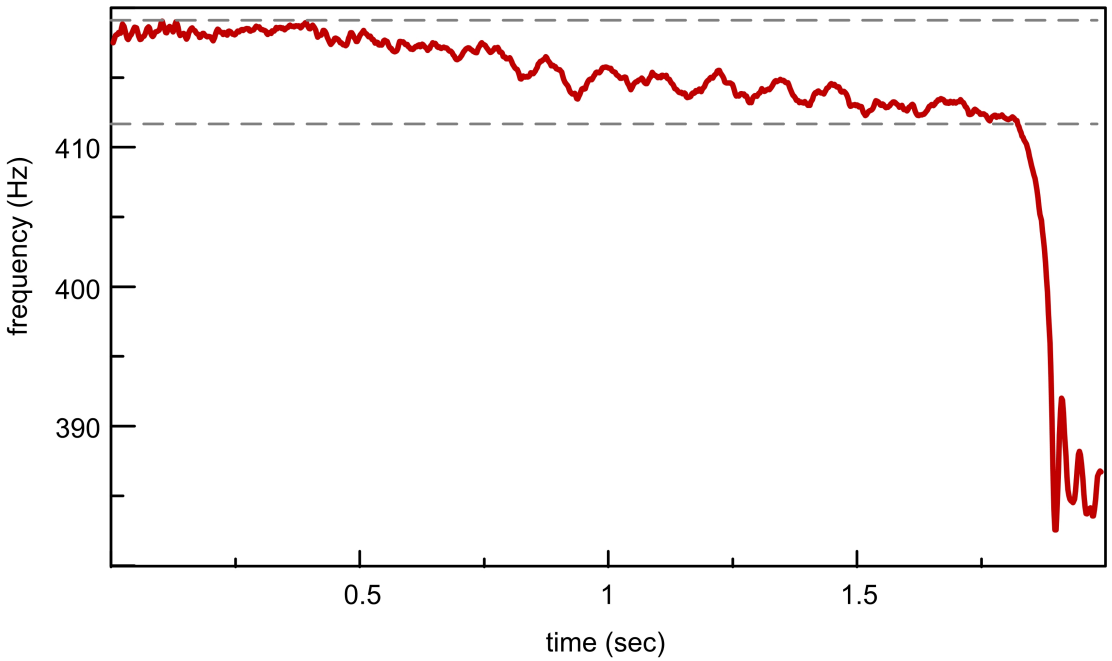


Figure 4.16: Graph showing the change in pitch as the eleventh resonance is lipped downwards until it drops to the tenth resonance, played on a horn by the maker Sandbach (GB.E.u, 203). Dashed lines indicate approximate maximum and minimum frequencies on the eleventh resonance.

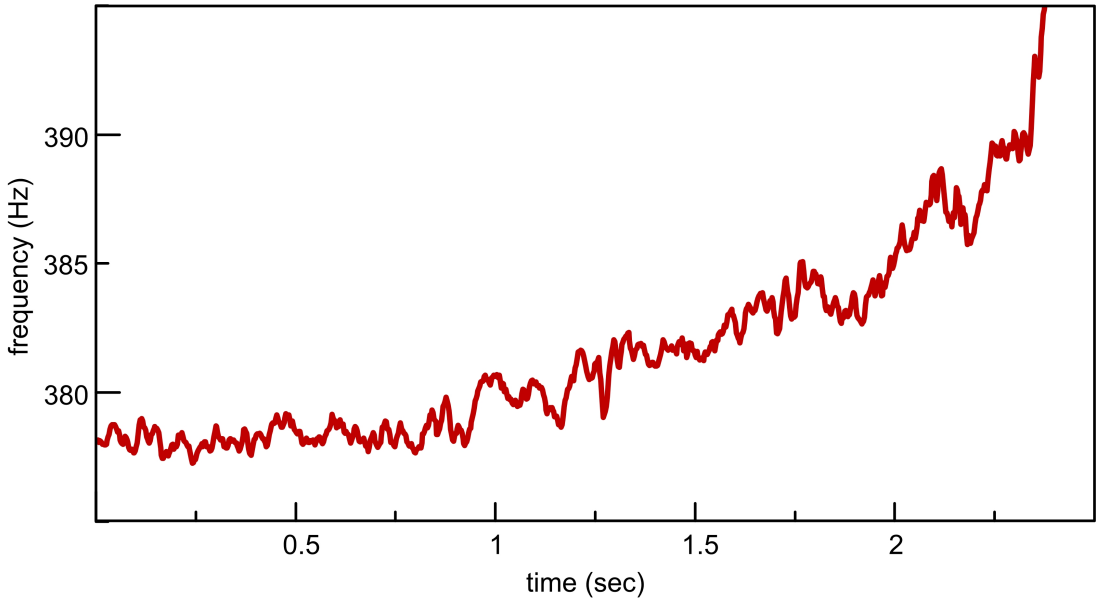


Figure 4.17: Graph showing the change in pitch as the eleventh resonance is lipped upwards until it rises to the twelfth resonance, played on a horn by the maker Hofmaster (GB.E.u, 3296).

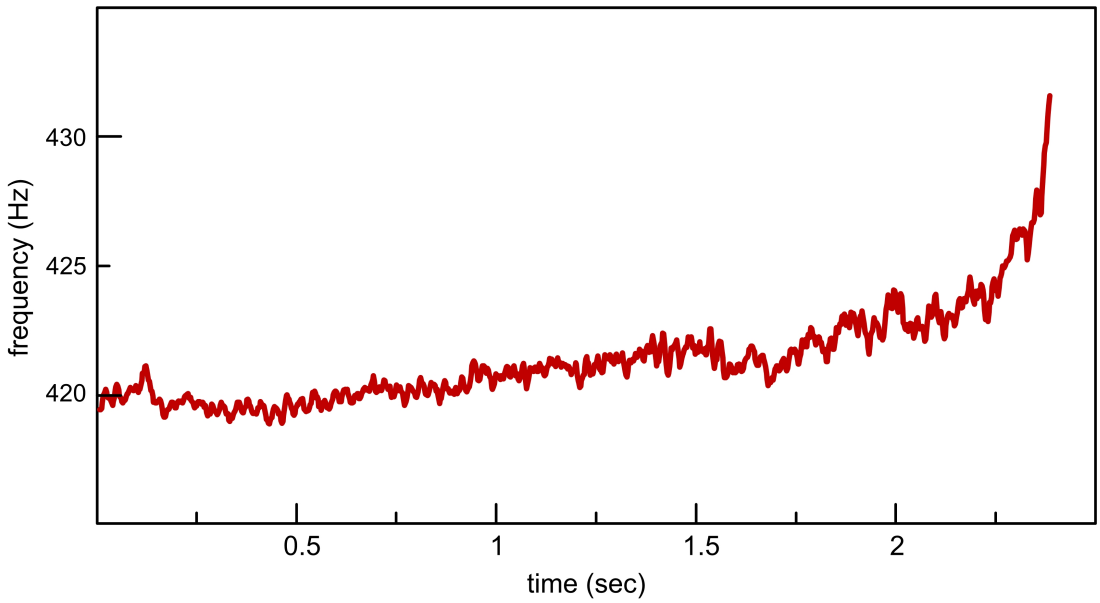


Figure 4.18: Graph showing the change in pitch as the eleventh resonance is lipped upwards until it rises to the twelfth resonance, played on a horn by the maker Sandbach (GB.E.u, 203).

a brass instrument, it is always interesting to examine acoustic input impedance curves, which provide some information about the strength and positioning of the resonances on an instrument. The quality factor, or Q factor, of each peak can also be determined from the input impedance curve and is an indication of the bandwidth of a particular resonance (more information about how to calculate Q values can be found in Section 4.3.1).

The Q factor is relevant to this discussion on pitch bending because it has been discovered that high values of Q, i.e. narrow peaks, make pitching notes on a brass instrument more difficult; narrow peaks result in a smaller 'target' frequency range for the player to aim for [Plitnik & Lawson, 1999]. On the other hand, one might deduce that a low Q factor could make lipping easier on the horn because there is a wider frequency range, but initial comparisons between the Q values of the eleventh resonant mode and player tests have revealed that a trend was not immediately apparent (see Appendix C). In the specific case of the Hofmaster and Sandbach comparison, the Q values of their eleventh resonance were found to be similar: Hofmaster, 22.5 and Sandbach, 22.3 (further discussion of this topic in the context of hand technique can be found in Section 4.3).

It seems likely however, that another aspect of the acoustics of the instrument might be helpful in indicating pitch bending potential: the location and strength of modes of resonance near higher spectral component frequencies, particularly those in the region of the second harmonic. The strength of the resonance in the region of the second harmonic plays an important role in supporting the fundamental pitch of the sounded note and it is exactly twice the note frequency. The second harmonic of the eleventh mode therefore, corresponds to a frequency in the region of the twenty-second resonance. It is in this range that the impedance curves of the Hofmaster (GB.E.u, 3296) and Sandbach (GB.E.u, 203) differ most significantly. The graph in Figure 4.19 shows the input impedance curve for the Hofmaster horn, and for comparison, the curve for the Sandbach instrument is shown in Figure 4.20, both measured without the hand in the bell.

In both graphs, the exact frequency of the second harmonic is indicated by the arrows on the right. The Hofmaster horn clearly has much stronger resonances in this region than the horn by Sandbach. The positioning of these peaks is also of

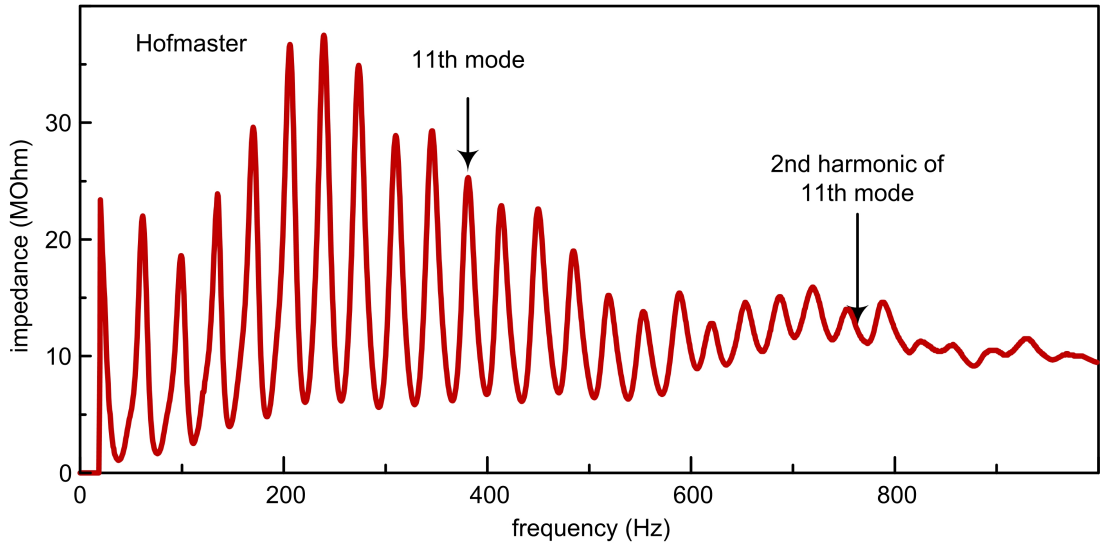


Figure 4.19: Input impedance curve measured (without the hand in the bell) on a horn by Hofmaster, from the mid-eighteenth century (GB.E.u, 3296). The frequency of the 2nd harmonic of the 11th mode is indicated.

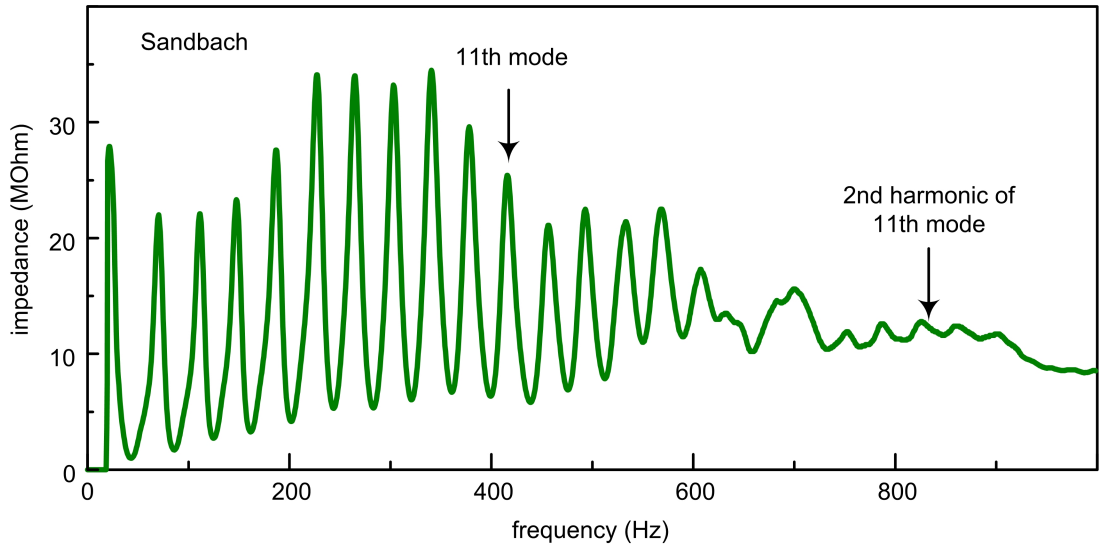


Figure 4.20: Input impedance curve measured (without the hand in the bell) on a horn by Sandbach, from the early nineteenth century (GB.E.u, 203). The frequency of the 2nd harmonic of the 11th mode is indicated.

importance, as it is likely that these resonances play a potentially vital role in supporting the oscillation of the lip as the player forces the frequency of the pitch away from the natural resonance of the air column. The higher resonant peaks for the

Hofmaster horn seem to fall at frequencies which might provide potential support to the fundamental during lipping, but for the Sandbach instrument there is very little potential for extra support because the peaks are so weak. This might also explain why the intensity was more easily maintained on the Hofmaster horn than on that by Sandbach. It should be noted that, during a pitch bend, the frequency of the second harmonic changes at twice the rate of the fundamental.

4.2.4 Spectral frequency

Further exploration concerning the link between lipping and resonances in the upper harmonic region involved the examination of the spectral content of a tone during the pitch manipulation process. Figure 4.21 shows an image of the varying spectral content measured in the mouthpiece of the horn during a pitch bend on the fourth resonance as it is lipped upwards. The instrument under analysis is the horn by the maker Hofmaster (GB.E.u, 3296). The vertical axis displays the harmonic frequency range from 0 to 2000 Hz. The horizontal bands correspond to the harmonics of the note D_3, where the darkest shade of grey indicates highest intensity and lighter shades of grey show lower intensity. Time is displayed from left to right with the far left of the image corresponding to the spectrum of the note played normally (without lipping). As time increases, so too does the pitch and in this example, the pitch varies by approximately half a semitone.

Initial observation of the spectrogram in Figure 4.21 indicates that as the note is lipped upwards in pitch, the harmonic content of the tone weakens slightly, particularly the strength of the second harmonic. A general observation from the musicians when carrying out this playing test, was that although the fourth resonance felt reasonably flexible to manipulate, increasing resistance was encountered when moving away from the centre of the note. This is not surprising given that the lips receive less support from the air column as the pitch strays further from the natural resonance of the instrument.

What is particularly interesting about the graph in Figure 4.21 however, is that a number of diagonal bands (at approximately 45° angles) of weaker intensity are

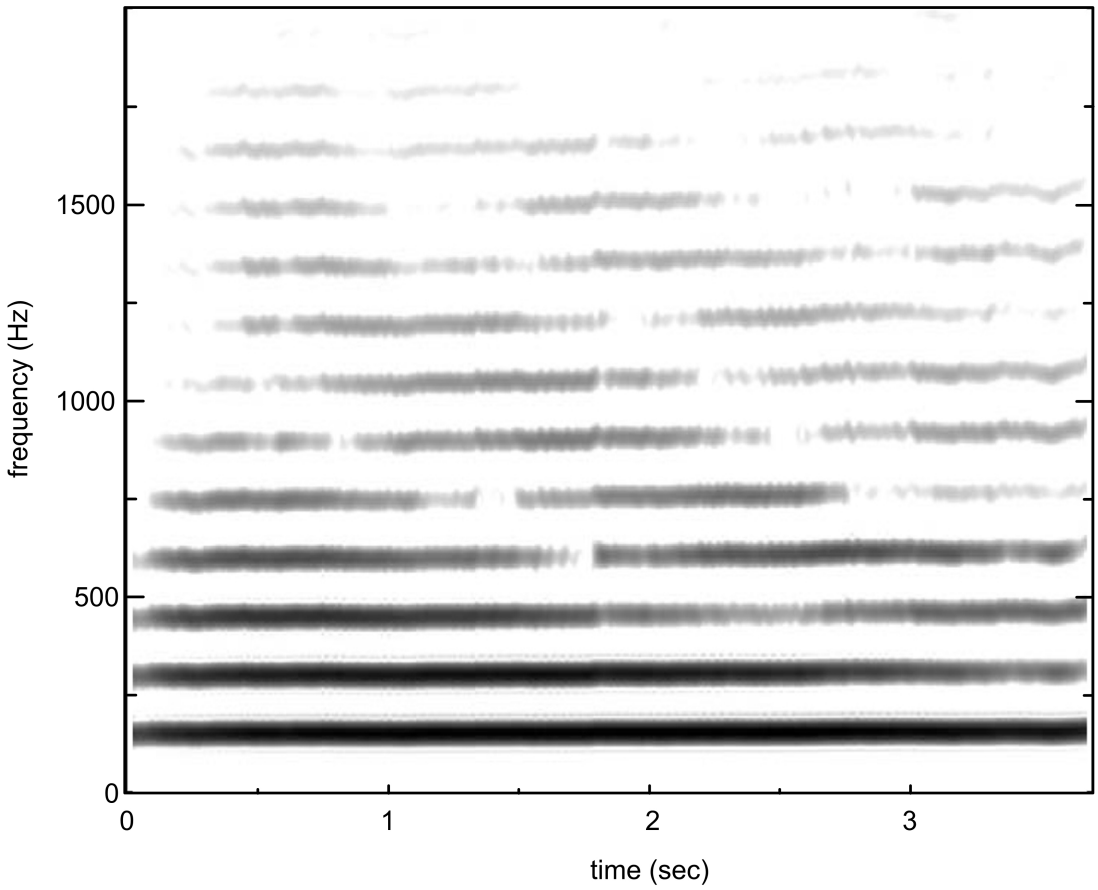


Figure 4.21: Graph showing the change in intensity of the spectral components as the fourth resonance is lipped upwards, played on a horn by the maker Hofmaster (GB.E.u, 3296), mouthpiece pressure signal.

also apparent in the spectrum. It is possible that these temporary harmonic weaknesses occur when there is very little support from higher modes of resonance in the corresponding region. This hypothesis is supported by the fact that the spectrogram shows the intensity of the higher harmonics (above about 1000 Hz) varying more frequently than for example the fundamental or second harmonic which remain nearly constant throughout the pitch change. The fundamental frequency rises in pitch by about 5 Hz, meanwhile the frequency of the sixth harmonic varies by about 30 Hz.

This characteristic fluctuation in spectral content was more pronounced in measurements of the mouthpiece pressure but was also observed to some extent in the radiated sound too. The waterfall plot in Figure 4.22 shows the spectrum of

radiated sound taken from the same recording as displayed in Figure 4.21; it shows the fourth resonance being lipped upwards. Time is shown as increasing from the

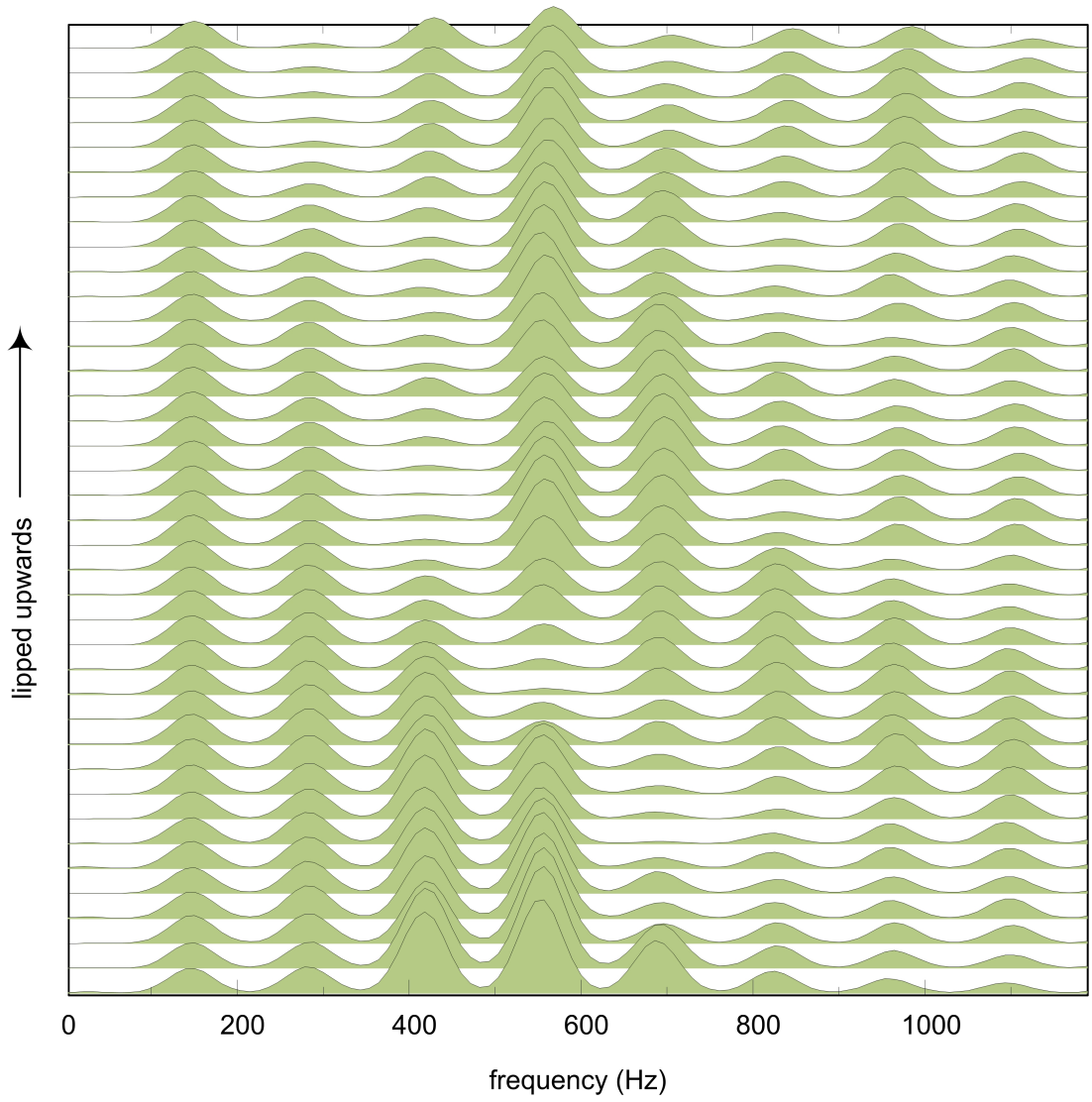


Figure 4.22: Graph showing the change in intensity of the spectral components as the fourth resonance is lipped upwards, played on a horn by the maker Hofmaster (GB.E.u, 3296), radiated pressure signal.

front to the back of the graph, and the frequency of the harmonics increases from left to right. The heights of the peaks give an indication of their strength. As in the previous graph (Figure 4.21), a similar pattern can be observed here amongst the harmonics, where they appear to drop in intensity in a seemingly orderly fashion; first the fifth, then fourth, third, etc.

At the point of maximum upward bend (towards the top of the graph in Figure 4.22), where the note is on the verge of jumping to the next highest resonance, the frequency spectrum is characteristic in that the second harmonic is considerably weaker than those immediately higher. By this point in the pitch bend, the fundamental frequency has risen from approximately 136 Hz to 141 Hz. This means that in order for the air column resonances to provide potential support to the oscillation of the lips at this higher (lipped) frequency, it might help if there was a strong resonance in the region of 282 Hz (twice the fundamental). At this point on the impedance curve for the Hofmaster horn however (see Figure 4.19), there are no strong resonances as this frequency lies close to the trough in between the eighth and ninth resonances. From these graphs it can be seen that the timbre of the note changes quite significantly due to the varying harmonic spectral content of the note and this can be heard as a general brightening of tone quality.

Another intriguing aspect of embouchure-controlled pitch manipulation concerns the difference between upward and downward pitch bends; players mostly felt that moving downwards, away from the centre of the note was easier than lipping it upwards. A difference was also observed when analysing the frequency spectra; the intensity of the harmonics for the downward pitch bend did fluctuate slightly but there was no obvious systematic pattern like the diagonal lines shown in the previous graphs of upward lipping. On a related project, research carried out by Chick & Logie [2009] concerning upward and downward lip slur transients also revealed that there were interesting differences between the pitch increasing compared to the pitch decreasing between notes.

4.2.5 Summary and further work

Investigations into the effect of different mouthpieces on the embouchure technique of lipping showed no one design to have a significant advantage over any other when testing the extremes of pitch flexibility. On the other hand, players certainly felt a difference in response between the three mouthpieces examined, and it was noted that the timbre varied audibly.

Initially, these results seemed rather surprising, but after looking at the impedance curves of the three mouthpieces on the same test horn, it was apparent that although the impedance curve envelopes differed significantly, there was very little difference between the location of equivalent resonant frequencies, i.e. the graphs from the three mouthpieces shared an almost identical set of harmonically related resonances.

This similarity of harmonicity was not found to the same extent when comparing the acoustic impedance of a number of early horns, tested using the same mouthpiece. In addition, the results from the horn comparison playing tests revealed that some horns responded more easily to pitch manipulation with the embouchure than others.

Closer analysis of the various impedance curves from the small sample of horns tested showed no obvious link between ease of lipping and the Q value of a specific resonance. Instead, it has been suggested that potential pitch flexibility of a note might depend to some extent on the location and strength of resonant peaks in the region of the second harmonic. The potential support provided by these upper resonances might also explain why players found it easier to maintain the dynamic intensity of some notes more than others, as the pitch was lipped away from the centre of the note.

Observation of pitch bending analysis on lower modes of resonance such as the fourth mode, showed interesting fluctuations in the contribution of higher modes of resonance to the sound spectra. It seems likely that the resonances of the air column influence the strength of the spectral content of a note to some extent during the process of embouchure pitch manipulation.

Although the results presented were largely inconclusive, it is possible that the players were compensating or readjusting their embouchure to some extent during the playing tests. Good players are extremely resourceful and it is likely that without meaning to, they adapt to different mouthpieces, or instruments, superimposing their own personal playing style on whatever they are faced with. For this reason, it would be useful to carry out tests with an artificial lip mechanism in order to remove player subjectivity.

It would also be interesting to broaden the scope of horns studied and compare early horns to their modern counterparts. Whereas pitch flexibility of notes on early brass instruments might have been seen as a desirable quality, today musicians are much more likely to pick a horn on which the notes feel very centred and stable.

The varying harmonic spectral content during lipping is also worth exploring in more detail. The horn players involved in these playing tests described making quite significant changes to the shape of the oral cavity as they attempted to manipulate the pitch of the note. Studies into the role of the vocal tract in didgeridoo playing have revealed that the player makes subconscious movements with the glottis to accentuate timbral variation [Tarnopolsky *et al.*, 2005] and it is possible that brass players might do a similar thing when trying to manipulate the pitch with their embouchure.

Analysis of the acoustic impedance proved to be a useful tool for assessing the lipping potential of different horns, but a more systematic approach would be valuable, looking at comparing exact values for the amplitudes of resonances at higher harmonic frequencies. This technique could also be used to explore the effect of introducing the hand into the bell of the instrument, a practice which is known to alter the upper resonant modes slightly (see Section 4.3 which follows) and may therefore have an effect on the lipping potential of a horn.

4.3 Hand

The adoption of hand technique revolutionised horn playing in the eighteenth century. Placing the hand within the bell of the horn allowed the player greater control over the pitch of notes but there are other effects too; a well positioned hand can increase security in the high register by strengthening the resonances in this region [Benade, 1990, pp. 427-428]; the hand also alters the timbre of the horn sound.

The possibility for the player to easily manipulate and fine-tune the pitch of the

horn was perhaps the most compelling aspect of this new technique. As the hand is increasingly closed over the bell of the horn, the pitch of the note drops. Seemingly counterintuitive to this, the new series of notes available to the player with the hand fully stopping the bell of the horn is approximately a semitone higher than the natural resonances of the instrument when fully open.* This apparent disparity concerning the raising and/or lowering of pitch due to hand stopping has sparked much debate amongst both horn players and scientists over the years.

Acousticians today generally agree that both of these acoustic behaviours can be explained by thinking of the hand as a large acoustic mass at the open end of the instrument [Backus, 1968; Pyle, 1964]. Coupled with the instrument, this added mass effectively lengthens the air column of the horn, lowering the pitch of the natural resonances to a frequency about a semitone higher than the next lowest 'open' note. A similar effect has been studied by Wachter [Wachter, 2008] in his diploma thesis, where he focusses on examining the acoustical implications of using a modern device to cover over the bell of a horn: a stopping mute.

Increased security in the high register due to the hand in the bell is an effect many horn players are unaware of. Also, the extent to which the hand is influential to the acoustics of the horn varies from instrument to instrument. In the early eighteenth century, composers were particularly keen to utilise the upper register of the brass instrument's range because in this region (often referred to as the clarino register) there was greater potential for melodic writing. An example of such writing can be seen in Figure 4.23.

Figure 4.23: A short excerpt taken from *Capriccio I* in D major (ZWV 182) by Jan Dismas Zelenka (1679-1745), showing extremely high horn writing up to the 24th mode, composed *c*1717.

This excerpt shows eight bars, taken from the first horn part of *Cappricio I* in D major by the composer Jan Dismas Zelenka. The highest note in this passage is G_6,

*For a horn in F of approximate length, 3.6 m.

the twenty-fourth mode of resonance on a horn crooked in D, and it occurs several times in the music. The range of notes in this passage is not an isolated example; throughout the whole of this work, Zelenka writes for the first horn in a similar range, almost entirely within the octave covering modes twelve to twenty-four. It is likely that this work was written with the talents of specific horn players in mind. Zelenka (1679-1745) spent most of his working life at the court of Dresden where there were some extremely talented horn players in residence.

Dresden was at the forefront of music making in the early eighteenth century, attracting virtuosic musicians from across Europe, but composers elsewhere were also pushing the 'upper' boundaries of early horn writing, only to a slightly lesser extent. Analysis of note ranges in the horn parts by English composers such as Handel, Barsanti, and also those included in the Egerton manuscript collection, has revealed that the use of the upper register was again very much favoured. Horn players in England would have frequently been required to ascend as high as the sixteenth mode, for a horn crooked in F (a written high C_6).

However, in these stratospheric heights, there was also more potential for 'splitting' notes due to the lack of security with increasing pitch. Security improves with the introduction of the hand in the bell, largely because this has the effect of raising the cutoff frequency of the bell. Radiation from higher modes of resonance is reduced, thus increasing internal reflections. As a result stronger standing waves occur in the air column of the instrument, helping to support the oscillation of the player's lip at higher frequencies. On an impedance curve, this effect can be observed as an increase in the strength and definition of peaks above approximately the twelfth harmonic (this corresponds to a frequency of about 520 Hz, the cutoff frequency region for an open horn bell without the hand).

Linked to the explanation of increased security in the high register and the reduced radiation at the bell of the horn due to the damping effect of the hand, this also produces a slight muting of the tone quality. There is an audible difference in timbre between the bright sound from a fully open, uncovered bell, compared to the warmer, darker sound from a partially covered bell or the more nasal quality of a fully stopped tone.

One of the few pieces of research linking the acoustical effects of hand technique to historical investigations of early horn technique has been carried out by Robert Pyle [2006]. In his experiments he compared the responsiveness of French- and German-style hand horns to hand technique, and found that contrary to popular belief, the smaller throat of the French-style instrument does not appear to be more sensitive to hand technique than the German model.

But this is still an area of research that has not yet fully been explored. The work presented in the rest of this chapter focuses on the changing acoustics and design of eighteenth- and early nineteenth-century instruments, and what we can infer by way of playing properties based on impedance measurements taken with the hand both in and out of the bell.

Hand technique opened up, not just a whole new range of notes and tuning possibilities, but also a rich palette of timbral colour which was to remain a popular feature of this style of horn playing, helping to keep the technique alive long after the invention of the valve rendered it unnecessary.

4.3.1 Methods of analysis

One of the most effective ways to systematically and objectively observe the acoustic implications of hand technique is to examine the effect that the hand in the bell of the horn has on the acoustic impedance. A full description of the process of measuring acoustic impedance and its basic interpretation can be found in Section 4.1.3. This rest of this section describes more detailed methods of analysing two specific aspects of the impedance curve; for exploring security in the high register it is useful to look at the strength of resonances, and for exploring intonation and pitch change it is the harmonicity of the resonances which is most relevant.

Where possible, the same mouthpiece was used for all acoustic measurements: a commercially available Paxman-Halstead-Chidell (PHC 22). Although this is an example of a modern horn mouthpiece, it was felt that the purpose of the following experiments was to compare the acoustics of historic horns, not their mouthpieces.

It is likely that during the eighteenth century, many different shapes of horn mouthpiece were in use and some early eighteenth century brass players might even have doubled on trumpet and horn, perhaps retaining their own or similar mouthpiece when transferring between the two instruments. The results from the previous discussion on lipping showed that changes in the the dimensions of the mouthpiece can have a significant effect on the acoustic input impedance of the horn (Section 4.2.2 and Figure 4.14), and so it was desirable to keep the mouthpiece the same for all experiments.

Previous research has assessed the variability in acoustic measurements as a result of different players' hand positions in the bell of the horn, and the results showed very little variation [Chick *et al.*, 2004]. In this research, for all measurements involving the effect of the hand, the same player's hand was used and it was placed in a position of support within the bell of the horn, a normal hand position adopted by horn players today. Figure 4.24 shows a photograph of this placement. It is likely that during the period of experimentation with hand technique in the eighteenth century, many different hand positions were tried for different effects, but the placement shown in Figure 4.24 was chosen for the following experiments because it is an intermediate position; the hand is inside the bell of the horn but is not covering the opening completely. This is what is known as an open hand position.

It has already been noted that the presence or absence of resonant peaks on an impedance curve provides a reasonable indication of how easy it is to play in a particular register of the instrument, but for this research it was desirable to have a more precise indication in order to gauge the extent to which the hand is influential; the narrowness of a peak, also known as the quality factor, or Q factor, describes the bandwidth of a particular resonance and provides information about its strength. From the player's perspective, variation in Q factor might be perceived as how well-centred a note is to play [Barclay, 1998, p.11]. The following equation shows how the Q factor can be calculated for a symmetric resonant curve:

$$Q = \frac{\omega_0}{\omega_u - \omega_l}, \tag{4.2}$$

Figure 4.24: Photograph of the hand position adopted when taking measurements with the hand in the bell. An example of an open hand position.

where ω_0 is the frequency of a particular resonance and $\omega_u - \omega_l$ is the bandwidth (difference between the upper and lower frequency values) at half its peak power.

Previous research has shown that narrow resonant peaks, resulting in high values of Q, make pitching notes on a brass instrument more difficult than wider resonance peaks with lower values of Q because there is a smaller 'target' frequency range to aim for [Plitnik & Lawson, 1999]. The positioning of the hand in the bell

of the horn changes this aspect of the acoustics of the instrument significantly; not only do the magnitudes of resonances in the upper register increase, but so too does the Q factor. The relevance to the following discussion, is that an objective study looking at variation in the Q values on horns dated from throughout the eighteenth century may help to provide a new perspective on the question of early horn technique. In this investigation, the focus of analysis is on modes eight to sixteen, commonly used notes in horn writing from this period and the region where a diatonic scale is almost possible.

When analysing the data, the resonances in the upper register were split into two groups, and the average Q value for each group was measured on all horns: group one consisted of modes eight to twelve and group two, modes twelve to sixteen. Calculating the average Q values of these two groups was found to be more useful than looking at values of specific resonances in isolation because small perturbations (such as a crook fitting) can often affect individual resonances. Modes eight to sixteen were chosen because over this range, it is typical to see a rapid decrease in the amplitude of peaks on the impedance curve when measured without the hand in the bell, but it is also the range where the introduction of the hand in the bell strengthens these resonances significantly.

A common issue when comparing the playing characteristics and acoustics of different early horns, is how to compare instruments of different lengths; the various fixed-pitch instruments and crook combinations all have unique playing and tonal qualities, and indeed this is one of the attractions of the early instrument. Figure 4.25 shows how the average Q value of modes twelve to sixteen varies in relation to the nominal fundamental pitch of the horn.

There is clearly a trend that the higher the pitch of the instrument (or the shorter the horn), the lower the Q value for modes twelve to sixteen. Therefore, for the purposes of this study, an acoustic comparison was made only between instruments of similar length.

The hand positioned within the bell of the horn not only has the potential to help with pitching in the high register by increasing the Q value and magnitude of resonances in this region, but also to alter the pitch or frequencies of resonances.

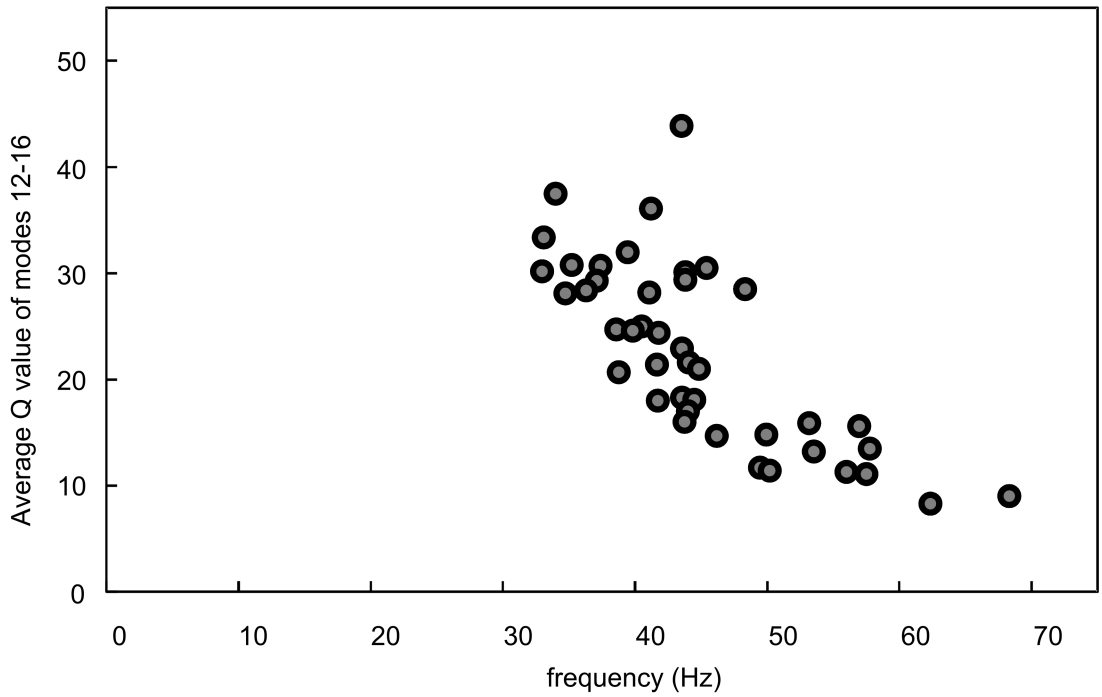


Figure 4.25: Graph showing the spread of average Q value for modes 12-16 plotted against nominal fundamental frequency for all horns.

A common word for referring to the relative pitches on an impedance curve is the harmonicity. The effect of the hand on intonation is more pronounced on some instruments than on others and may provide clues as to whether a particular horn was made with hand technique in mind or not.

A useful diagram for observing relative intonation is the harmonicity plot, which can be seen on the left in Figure 4.26 alongside information regarding the Q values of each resonance. The data for both of these graphs has been extracted from the impedance curve of a typical horn shown in Figure 4.27. The harmonicity plot provides a visual representation of how closely the natural resonances of an instrument are aligned to a harmonic series with a fundamental pitch based on the average of modes four and eight. A perfect harmonic series would produce a straight vertical line and deviation from this line is measured in cents.

In the plot shown in Figure 4.26, the fundamental pitch (the very lowest mode) is not visible as it is more than 100 cents (one semitone) flat. This flat tendency is a feature of many brass instruments but is not as problematic as it first appears

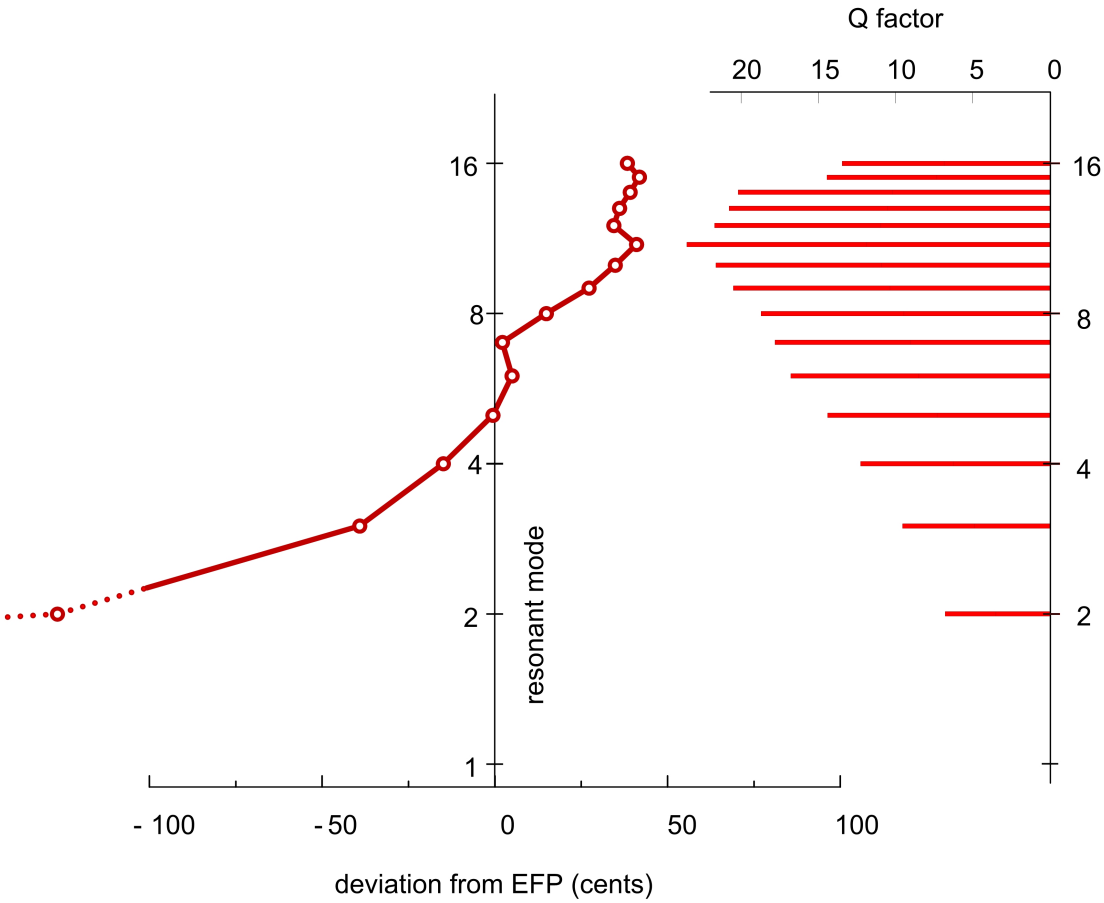


Figure 4.26: Harmonicity plot (left) and Q factor values (right) for a horn by Kretzschmann (GB.E.u, 531), from the early nineteenth century, crooked in D, measured without the hand in the bell. The data for this graph was extracted from the impedance curve shown in Figure 4.27

because in practice, at all but the quietest dynamic levels, low notes gain support from upper resonances and this effect often helps to bring lower notes more in tune. Higher pitches on the other hand are largely left unsupported as there are few, if any distinct resonances in their upper harmonic regions. It is also a common feature of many brass instruments for the higher modes to be sharp, as is the case here.

Deviation from the centre line of the harmonicity plot is not necessarily a negative feature. As mentioned previously, it may not be desirable for every note to fall within a harmonic series; the seventh, eleventh, and thirteenth modes do not fit

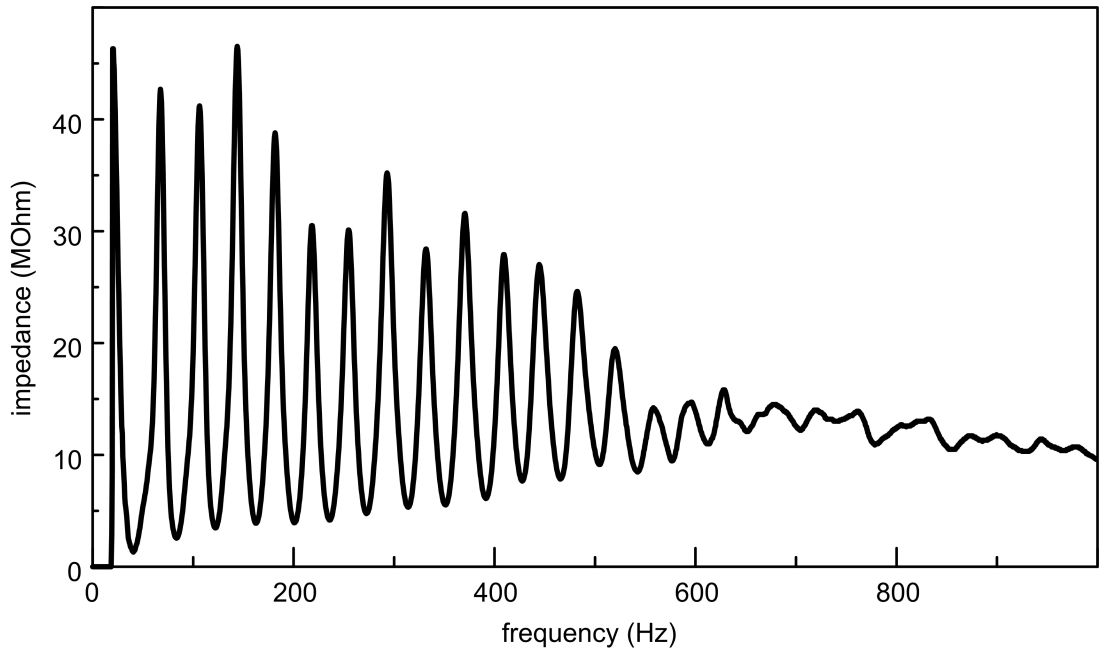


Figure 4.27: Input impedance curve measured on a horn by Kretzschmann (GB.E.u, 531), from the early nineteenth century, crooked in D, measured without the hand in the bell. A harmonicity plot and Q values based on this data are shown in Figure 4.26.

comfortably within tempered tuning systems. The eleventh mode for example, in its pure harmonic form, falls somewhere in between a written F_2 and $F_2^\sharp$. It is possible that eighteenth-century horn players may have favoured an instrument on which this particular resonance was closer to the $F_2^\sharp$, finding it easier to bend the pitch lower rather than higher.* Nevertheless, a horn that is considered to play well and have good intonation will normally produce a harmonicity plot with points that closely match a harmonic series.

4.3.2 Measurements *without* the hand in the bell

In order to discover which instruments might have been intended for use with the hand in the bell, it was first useful to compare the acoustics of all instruments without the hand in the bell, and to examine the difference between later dated horns

*Brass players generally find it easier to bend the pitch downwards when applying either embouchure technique or hand technique.

(intended for hand technique) and early horns (not intended for hand technique) models.

Baroque horn players were adept at playing in the very highest register of the horn (as seen by the horn writing in Figure 4.23) and they would most likely have preferred or favoured instruments which provided as much security in this region as possible. Acoustic impedance curves are useful for this area of analysis as they provide a relatively unambiguous indication of how easy it is to play in the high register.

An instrument which was definitely intended for use with the hand in the bell is a horn by the maker Charles Kretzschmann (GB.E.u, 531), dated from the early nineteenth century. The very end of the impedance curve for this instrument is shown in Figure 4.28 and for comparison, an earlier instrument from the mid-eighteenth century by the maker Hofmaster (GB.E.u, 3296) is shown below it in Figure 4.29. The date of the Hofmaster horn places it right in the middle of the period of great change with regard to hand technique and so there is some uncertainty about whether or not the hand would have been employed in the bell of this horn.

The instruments are both crooked in the common key of D and the part of the impedance curve shown is the highest playable resonances in the range of these horns. The frequently called on sixteenth resonance mode is annotated on both graphs, and for the Hofmaster impedance curve (Figure 4.29), defined peaks can be seen as high as the twenty-third resonance, a less common note in horn writing from this era, but nonetheless evident in first horn parts from the court of Dresden as seen previously (Figure 4.23). Comparison of these two graphs clearly shows that the Hofmaster horn has much stronger resonances from the sixteenth to the twenty-third modes than the instrument by Kretzschmann (Figure 4.28).

Playing tests comparing these two instruments confirmed that the lack of defined peaks in the region of the sixteenth to twenty-third modes for the horn by Kretzschmann indicate a lack of pitch definition when slurring between notes in this region. Analysis of playing tests was carried out using the pitch detection software 'Praat' (previous discussion of this method of analysis can be found in Section 4.2) and

examples of the analysis of sound clips from both instruments are shown in Figure 4.30.

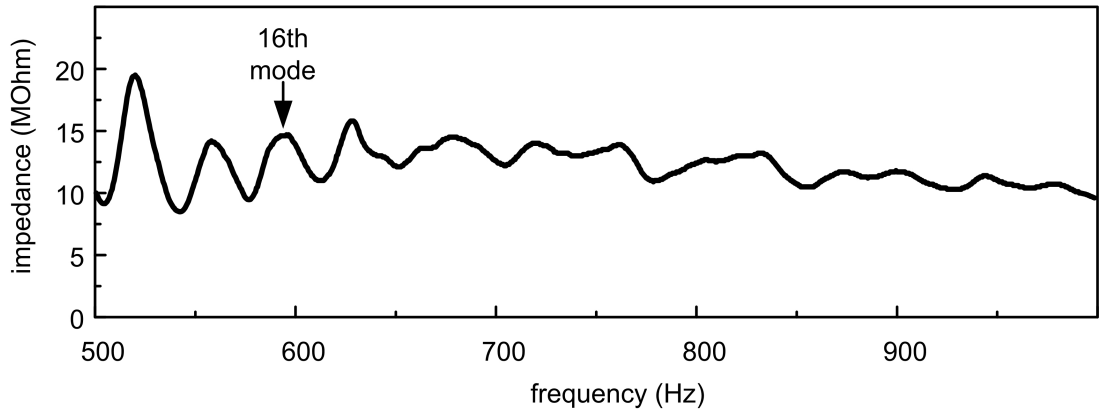


Figure 4.28: Input impedance curve showing the very high register of a horn by Kretzschmann, from the early nineteenth century (GB.E.u, 531), crooked in D, measured without the hand in the bell. The peak corresponding to the 16th mode is indicated.

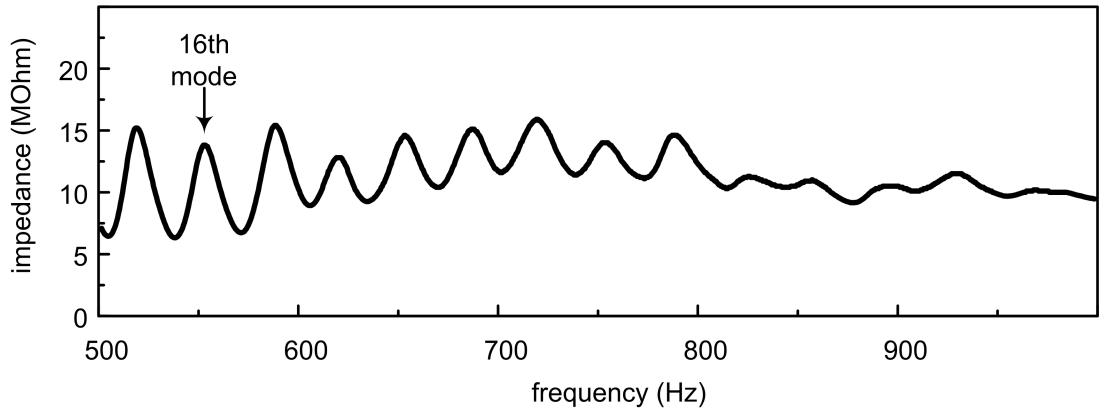


Figure 4.29: Input impedance curve showing the very high register of a horn by Hofmaster, from the mid-eighteenth century (GB.E.u, 3296), crooked in D, measured without the hand in the bell. The peak corresponding to the 16th mode is indicated.

In these sound samples, the player was asked to slur from the eighth mode of resonance upwards until the notes no longer felt distinguishable as separate pitches. The ascending scale on the Hofmaster horn (the left hand graph in Figure 4.30) shows that the pitches start to merge together above about 750 Hz, corresponding to approximately the twenty-second harmonic. For the instrument by Kretzschmann however (the right hand graph in Figure 4.30), the notes become

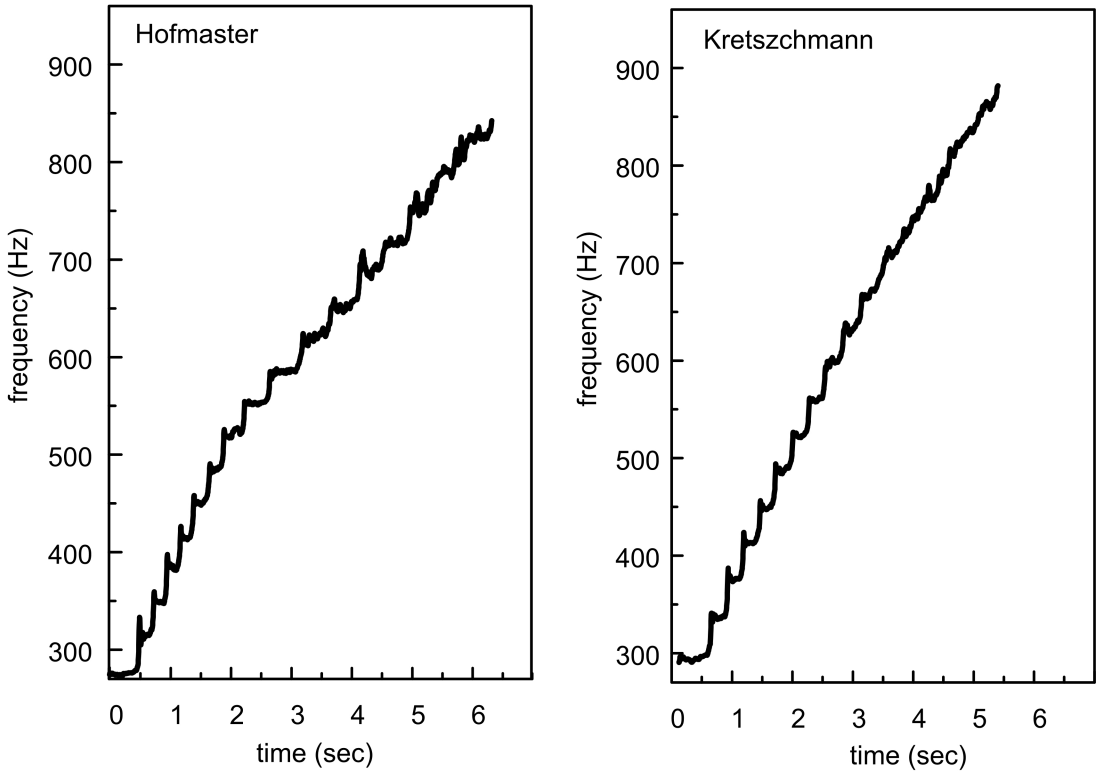


Figure 4.30: The transition between notes in the high register, starting on the 8th mode and slurring upwards through the resonances. Played on horns by Hofmaster (GB.E.u, 3296) (left) and Kretzschmann (GB.E.u, 531) (right) crooked in D, without the hand in the bell. More defined steps can be seen in the very high register of the Hofmaster example compared to that of Kretzschmann.

less clearly defined much lower in the scale at approximately 650 Hz, slightly higher than the seventeenth resonance. These results correspond well to the shape of the impedance curves and definition of peaks in the previous Figures 4.28 and 4.29.

Whilst the analysis of acoustic impedance curves and of player tests suggest that the horn by Hofmaster has a better high register than the horn by Kretzschmann (both without the hand in the bell), the Hofmaster instrument did not perform quite as well in this region when compared to a horn by the maker Nicholas Winkings, also dated from around the middle of the eighteenth century. Part of the impedance curves for the Hofmaster (GB.E.u, 3296) and Winkings (GB.E.u, 2492) horns can be seen in Figures 4.31 and 4.32.

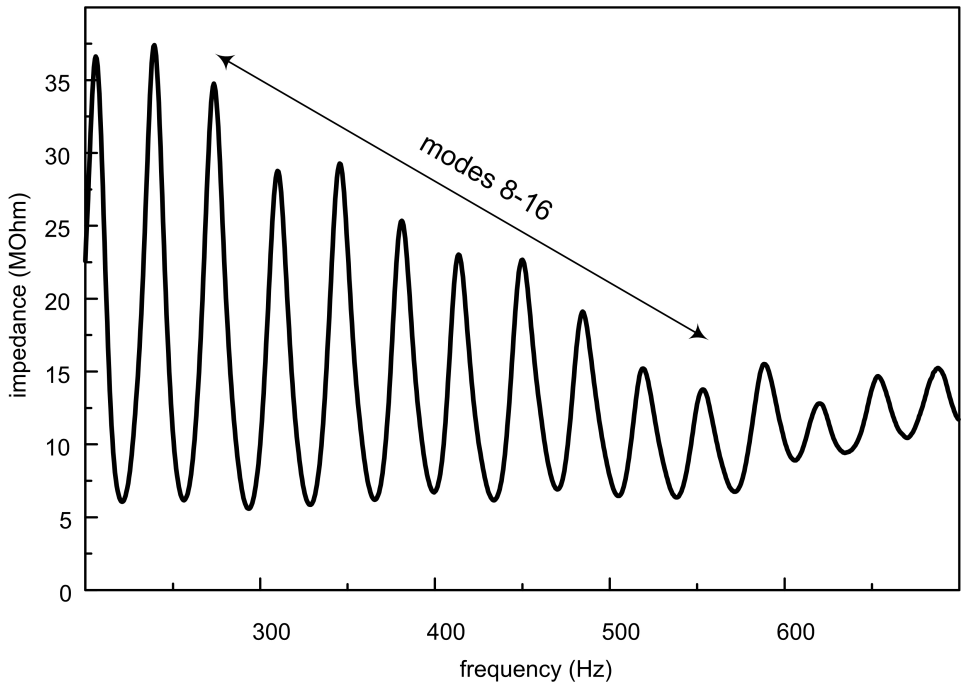


Figure 4.31: Input impedance curve showing the rate at which the peak amplitudes of the resonances diminish over modes 8-16 on a horn by Hofmaster (GB.E.u, 3296) from the mid-eighteenth century, crooked in D, measured without the hand in the bell.

Both instruments were measured without the hand in the bell and are pitched in D, but whereas the Hofmaster horn uses a crook and coupler system to achieve the appropriate length of tubing, the horn by Winkings is fixed pitch.

Comparison of their impedance curves shows a significant difference in the shape of the curves in the high register; the peak amplitudes of modes eight to sixteen on the Hofmaster instrument drop quite steeply whereas the maximum peak values for the Winkings horn in this range are reasonably level. A more even spread of peak values in this high range of the horn impedance curve might therefore indicate greater ease of playing in this register.

Playing tests similar to those described previously, confirm that the Winkings horn was generally felt to be more secure to play in the high register when compared to the instrument by Hofmaster. The reason for this may in part be to do with the strength of resonances in this region, but also perhaps to do with the rate at which

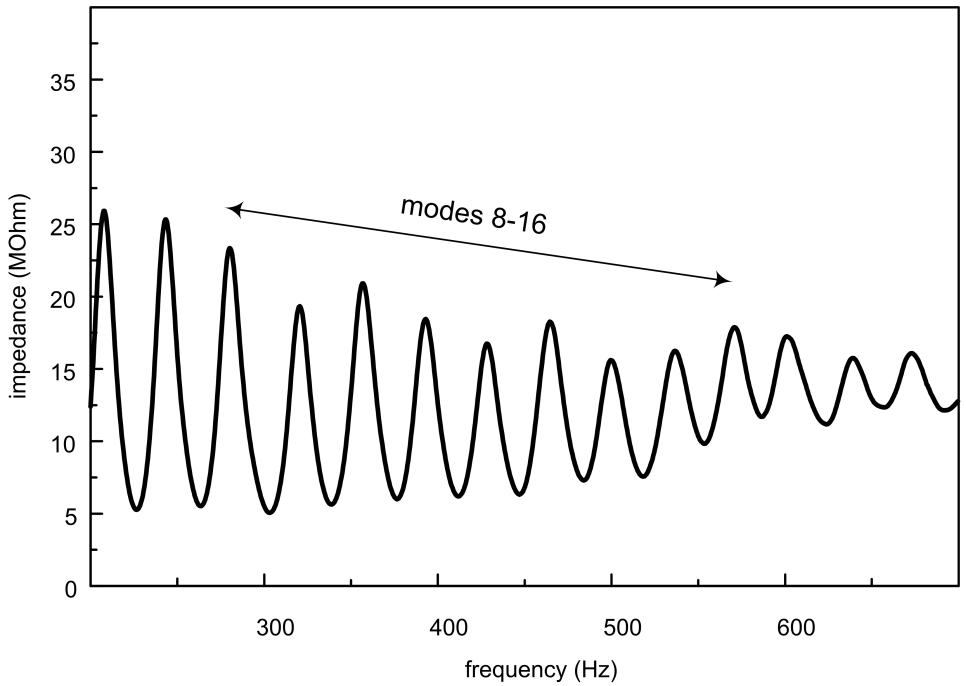


Figure 4.32: Input impedance curve showing the rate at which the peak amplitudes of the resonances diminish over modes 8-16 on a horn by Winkings (GB.E.u, 2492) from the mid-eighteenth century, crooked in D, measured without the hand in the bell.

the maximum peak amplitudes decrease over this range. This latter hypothesis is merely speculation but it would be interesting to explore this area further by analysing a broader range of instruments.

To summarise briefly, the horn by Kretzschmann (GB.E.u, 531) was found to be the least secure of the three instruments to play in the high register, but as an early nineteenth century orchestral horn, made to be played with crooks, hand technique, and in a lower register of the instrument than had previously been the case, this result is not surprising. The horn by Hofmaster (GB.E.u, 3296), also a crooked instrument, responded better in the high range but not as well as an instrument by Winkings (GB.E.u, 2492) which is fixed pitch, has a larger corpus diameter, and was likely to have been made without hand technique in mind. Further evidence that the Winkings horn was probably not intended to be played with the hand in the bell concerns the practical aspect of ergonomic comfort; the larger corpus diameter would have made it quite awkward to play

with the hand in the bell, however the positioning of the bell on the Hofmaster and Kretzschmann instruments is located much more conveniently (more detailed ergonomic analysis is described in Chapter 5).

In general, it was discovered that the impedance curves for horns from the early to mid-eighteenth century were characterised by relatively strong resonances across modes eight to sixteen and beyond. On the other hand, instruments from the late eighteenth and early nineteenth centuries were lacking defined peaks across this range. It was common for composers to use modes as high as the sixteenth in their horn writing throughout the period of the eighteenth and nineteenth centuries, and yet the impedance curves for a number of instruments (measured without the hand in the bell) show extremely weak resonances in this region. The next section (4.3.3) looks at the importance of the hand in improving security in the high register of horns such as these.

This chronological trend with regard to ease of playing in the high register was explored further by analysing the Q values of the resonances. A similar pattern was revealed but with two separate groups emerging. In the first group, consisting mainly of horns from the early to mid eighteenth century, the instruments were generally found to have slightly lower Q values across modes eight to twelve (quite high in the range of a horn) than those in the second group, which was largely made up of horns from the late eighteenth and early nineteenth centuries. Perhaps a more significant characteristic in defining these two groups was that the earlier instruments (in group one) frequently displayed higher values of Q above mode twelve.

To highlight the difference between the acoustics of instruments from each group, a comparison is shown in Figure 4.33. These impedance curves have been discussed previously (Figures 4.28 and 4.32) and are from two very different instruments by the makers Winkings (GB.E.u, 2492) and Kretzschmann (GB.E.u, 531), but in this Figure the curves have been superimposed in order to show the variation in the high register from modes eight upwards. The difference between these two horns can be seen more clearly by comparing the harmonicity plots and Q values as shown in Figure 4.34.

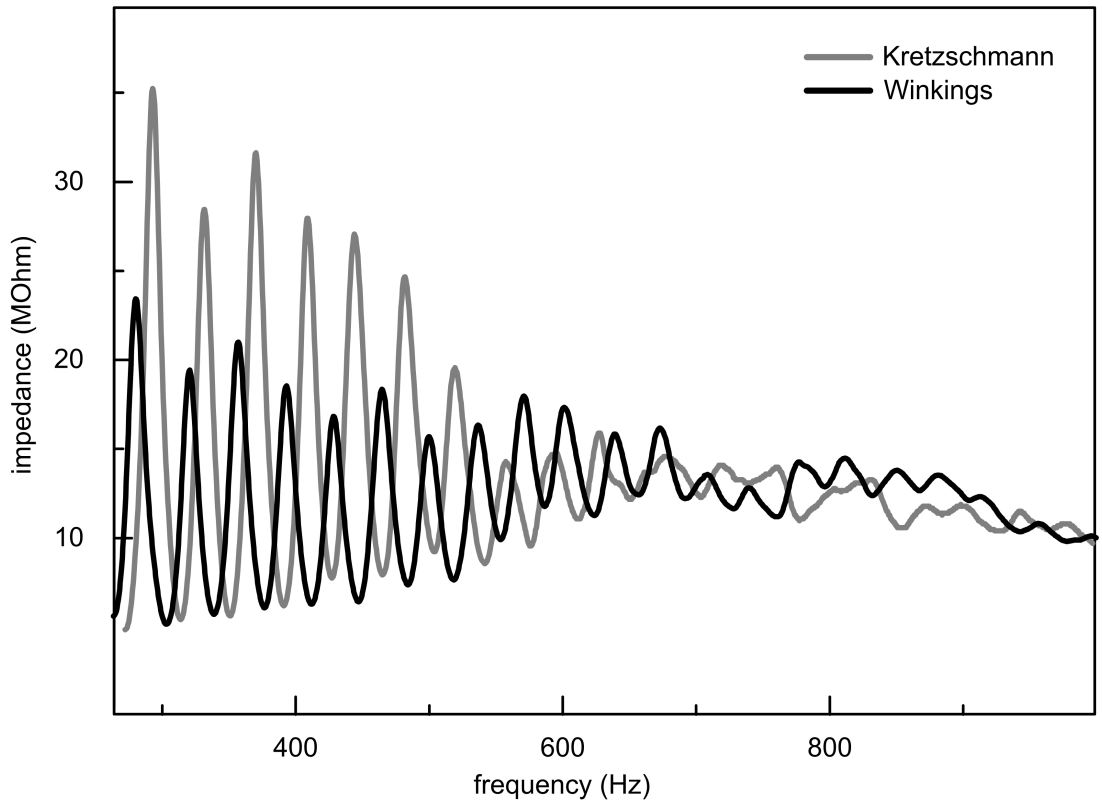


Figure 4.33: Input impedance curve comparison of two horns by makers Kretzschmann (GB.E.u, 531) and Winkings (GB.E.u, 2492), crooked in D, measured without the hand in the bell. Only the resonances from mode 8 upwards are shown.

The harmonicity plots (on the left) show that the resonances in the high register of the Winkings horn (in blue), from modes eight to sixteen, are reasonably close to being harmonically aligned, although overall slightly sharp compared with the rest of the instrument. The upper resonances for the horn by Kretzschmann (in red) on the other hand, begin to drift sharp above the seventh mode and then become significantly sharper above mode seventeen where the peaks are now extremely weak. The Q value chart (on the right) shows that in the low to moderately high range of the horn by Winkings, the Q values are lower than on the instrument by Kretzschmann, but above mode fourteen this changes and the Winkings horn now has higher values of Q.

If a horn player were to be asked which of these instruments they would prefer to play in the high register without the hand in the bell, the Winkings horn would

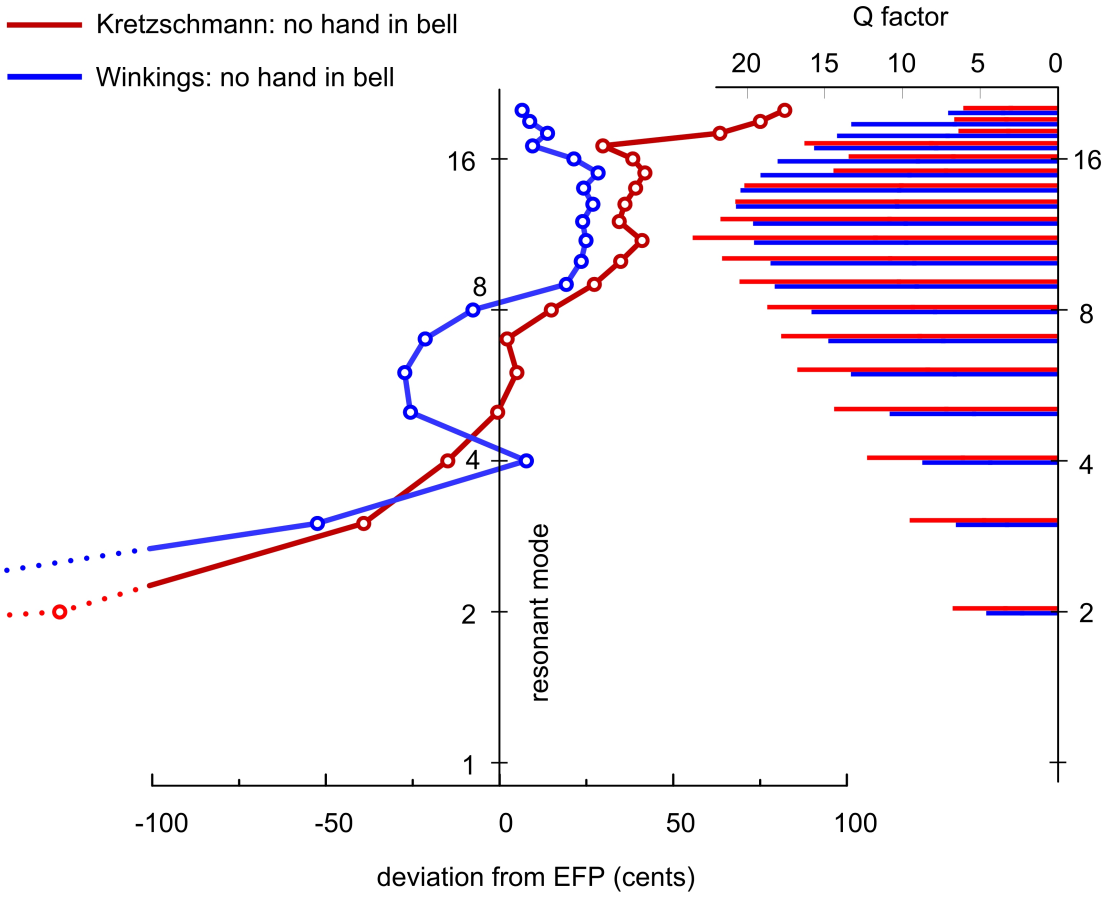


Figure 4.34: Harmonicity plot (left) and Q factor value (right) comparison between a horn by Kretzschmann (GB.E.u, 531), from the early nineteenth century, and a horn by Winkings (GB.E.u, 2492), from the mid eighteenth century. Both instruments were crooked in D and the measurements were taken without the hand in the bell.

most likely be the preferred choice, based on these results, but as the next section will reveal (4.3.3), this might change if the player were to be allowed to place their hand in the bell of the horn.

4.3.3 Measurements *with* the hand in the bell

Modern horns are designed such that they provide optimal performance with the hand placed in a position of support inside the bell of the instrument. As playing technique changed during the eighteenth century, instrument makers adapted the

design of their horns to suit the new method of playing with the hand in the bell. Without the technology for measuring the acoustical effect of this technique, early horn makers would have relied on trial and error to produce the best instruments for the purpose. With the advantage of hindsight, it is interesting to analyse the change in horn design over the eighteenth century, to see if this can shed light on which instrument might have been intended for which technique. The effect of the hand in the bell influences the acoustics of some instruments more than others and the rest of this section examines this aspect in more detail.

Previously, in Section 4.3.2, a horn by the maker Kretzschmann (GB.E.u, 531) was featured as an instrument with relatively weak resonances in the high register when played without the hand in the bell. It can be assumed however, that this instrument was intended to be played *with* the hand in the bell because it is from the early nineteenth century, by which period, hand technique had largely become standard practice in the concert setting. Peaks in the upper region of the impedance curve for the Kretzschmann horn change quite significantly with the introduction of the hand into the bell, as can be seen in Figure 4.35. The increase in strength of the higher resonances due to the effect of the hand can clearly be seen but there is almost no change concerning the lower modes.

One of the main effects of the hand is to slightly lower the pitch of the upper resonances. This can be seen to some extent on the superimposed impedance curves (Figure 4.35) but is more clearly depicted by comparing harmonicity plots as shown on the left in Figure 4.36. The characteristic sharp drift is much less pronounced due to the effect of the hand, and the resonances are now more harmonically aligned. The increase in the definition of peaks in the high register results in higher Q values as shown by the comparison chart on the right in Figure 4.36.

The question posed previously as to whether a horn by Winkings or by Kretzschmann would be easier to play in the high register, becomes a less obvious choice when hand technique is considered. The previous graphs (Figure 4.34) indicated that the Winkings horn might be a safer option for high register playing, based on information about both harmonicity and Q values, but with the hand placed in the bell of the Kretzschmann horn, the results are much more similar, see Figure 4.37.

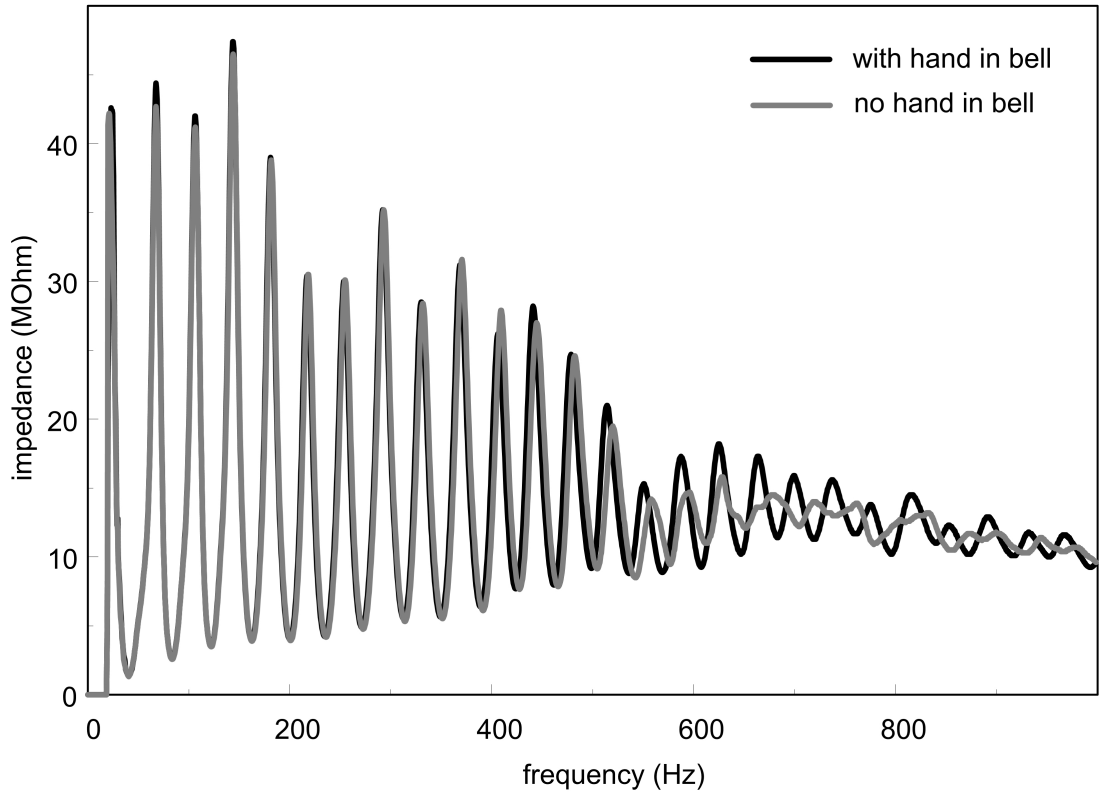


Figure 4.35: Input impedance curve comparison of a horn by Kretzschmann (GB.E.u, 531), from the early nineteenth century, crooked in D, measured with and without the hand in the bell. The graph shows significant variation in the high register (see Figure 4.36 for harmonicity plots and Q values relating to this data).

As mentioned previously, there is little doubt that the Kretzschmann horn would have been played using hand technique, and this is supported by the acoustic analysis shown. An instrument for which there is greater uncertainty surrounding how it might have been played, is a mid-eighteenth horn by the maker Hofmaster, which was also discussed previously in Section 4.3.2. When crooked in D, this horn was found to have relatively strong resonances in the upper register (see Figure 4.29) which might suggest that the hand was not a necessary requirement to provide additional security in this range. However, when crooked in F (without the hand in the bell), this instrument does not appear to have such a strong high register, demonstrated by the impedance curve in Figure 4.38. Peak definition around the sixteenth resonance in particular is lacking, suggesting that this commonly required note would perhaps be difficult to play with any any confidence.

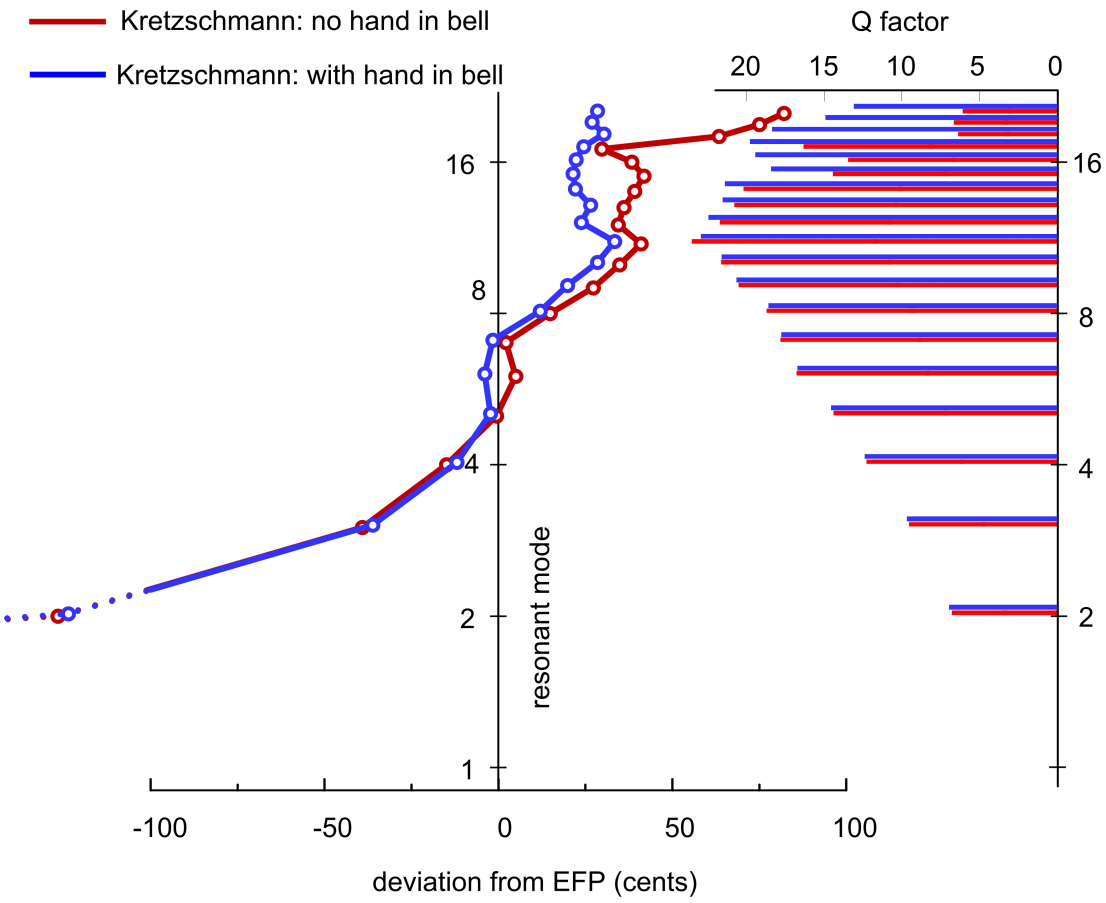


Figure 4.36: Harmonicity plot (left) and Q factor value (right) comparison between a horn by Kretzschmann (GB.E.u, 531), from the early nineteenth century, crooked in D, measured with and without the hand in the bell (see impedance curve in Figure 4.35).

The addition of the hand in the bell of the Hofmaster horn has a noticeable impact on these weak resonances near the sixteenth mode, as shown by the impedance curve in Figure 4.39. In the region of 600-800 Hz, the resonant peaks are now significantly stronger, helping to provide support to the oscillation of the lips when playing the sixteenth mode, and also providing extra reinforcement for notes in the region an octave lower.

The Hofmaster horn was made in England at a time when composers were keen to utilise the high register of the instrument, certainly up to the sixteenth mode of resonance, but generally not as high as the horn parts from other regions of Europe such as Dresden. Given these requirements, it is possible that an eighteenth-

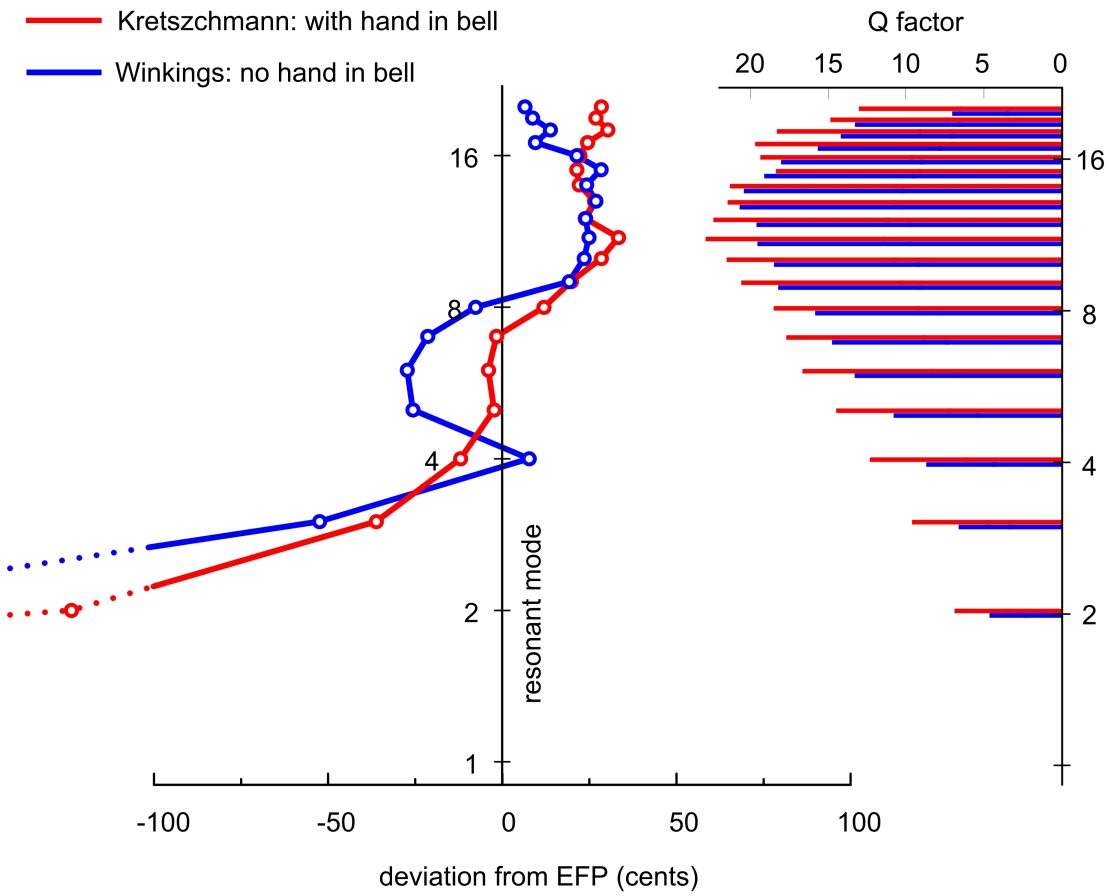


Figure 4.37: Harmonicity plot (left) and Q factor value (right) comparison between a horn by Kretzschmann (GB.E.u, 531), from the early nineteenth century, measured with the hand in the bell, and a horn by Winkings (GB.E.u, 2492) from the mid eighteenth century, measured without the hand in the bell.

century English player might have been reasonably happy performing on the Hofmaster horn crooked in D, even if he were not yet aware of the advantages of hand technique, but maybe less confident in the high range if it were to be crooked in F.

Similar analysis of all horns revealed several other instruments with notably weak upper resonances when measured without the hand in the bell, but after the introduction of the hand, a significant strengthening of higher mode resonances was seen. These include horns by the makers Saurle (A.KR.sk, Piz.005), Lausmann (A.KR.sk, Piz.006), and Shaw (A.KR.sk, 216). Indeed, these are all instruments dated from around the late eighteenth and early nineteenth centuries, a period

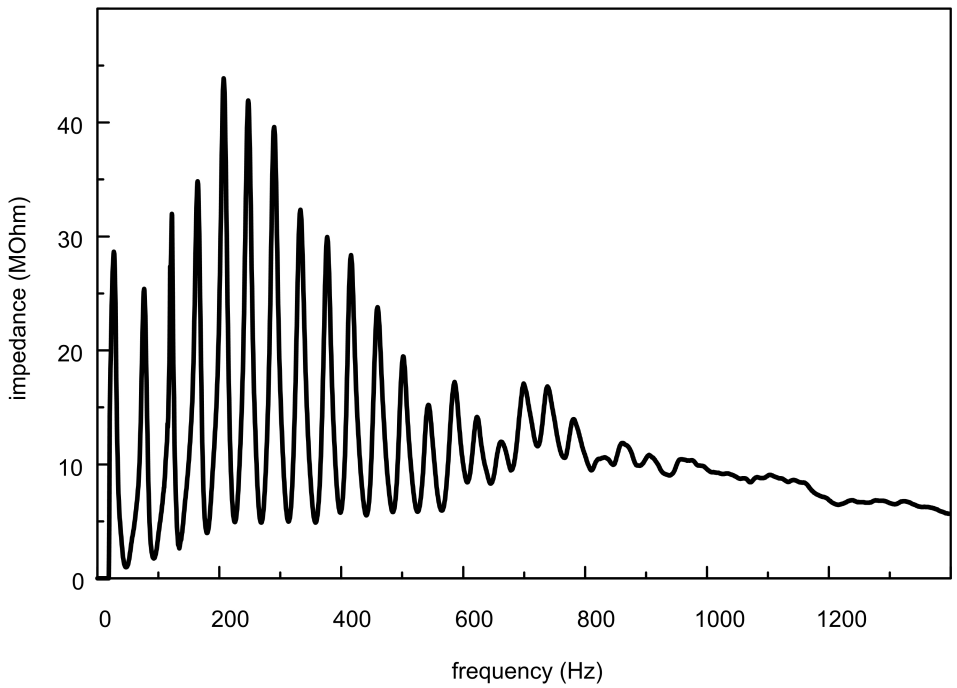


Figure 4.38: Input impedance curve measured on a horn by Hofmaster (GB.E.u, 3296), from the mid eighteenth century, crooked in F, without the hand in the bell.

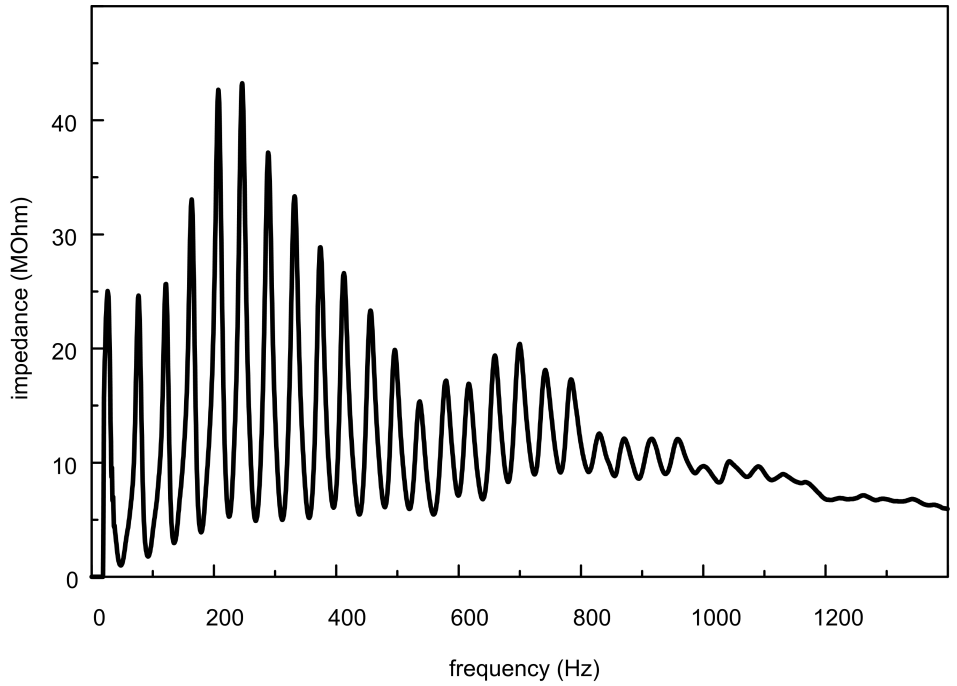


Figure 4.39: Input impedance curve measured on a horn by Hofmaster (GB.E.u, 3296), from the mid eighteenth century, crooked in F, with the hand in the bell.

when it was very likely that hand technique would have been used. Nevertheless it is interesting to observe such strong evidence to support the fact that without the hand in the bell, some of the notes in the high register would be almost impossible to play, and many of these resonances would also be extremely sharp, but with the hand placed in the bell, the peaks not only become stronger, but the frequency drops, bringing the notes more in tune.

A final example to demonstrate this effect can be seen in Figure 4.40, showing two impedance curves superimposed, for hand in and out of the bell on a horn by the maker Michael Saurle (A.KR.sk, Piz.005). A photograph of this instrument

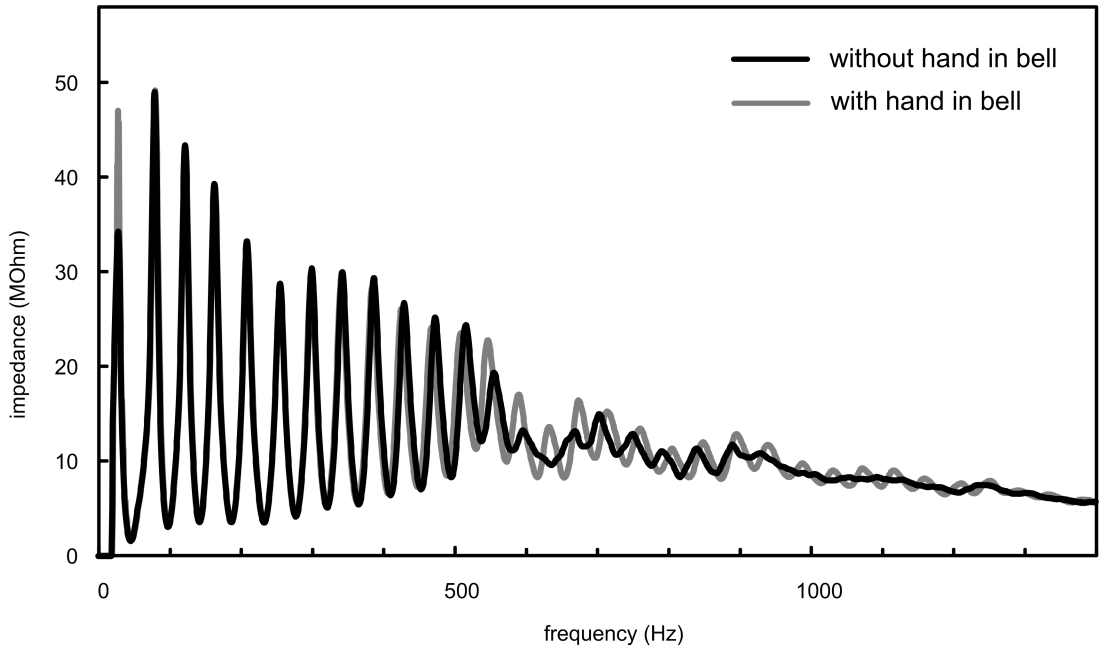


Figure 4.40: Input impedance curve comparison of a horn by Saurle (A.KR.sk, Piz.005), from the early nineteenth century, crooked in F, measured with and without the hand in the bell. The graph shows significant variation in the high register, particularly in the region of the 15th mode of resonance.

can be found in Figure 4.41. With the hand in the bell, the gap between the fourteenth and fifteenth resonances disappears and a peak is apparent. The pitches also become more harmonically aligned due to the flattening effect of the hand, and small resonant peaks can be seen extending beyond 1000 Hz.

So far, the examples shown have mainly been to demonstrate the significant role

Figure 4.41: Photograph of a horn by the Munich maker Michael Saurle, from the early nineteenth century (A.KR.sk, Piz.005).

that the hand plays in altering the acoustics of higher resonance modes, but on some instruments the hand has very little effect. Figures 4.42 and 4.43 show harmonicity plots for two very different horns; the crooked horn by Saurle already mentioned, and a simple coiled hunting horn dated 1718 by the maker Michael Leichamschneider (CH.B.hm, 1878.22.). In each harmonicity plot, the pitches of the resonances are shown with (continuous line) and without (dashed line) the hand in the bell.

The main difference between the effect of the hand on the acoustics of each horn (Figures 4.42 and 4.43) concerns the pitches in the high register, modes eight to sixteen. There is more deviation in the results concerning the horn by Saurle than in that by Leichamschneider. In a previous graph (Figure 4.40), the impedance curve for the Saurle horn (without the hand in the bell) showed that the fifteenth and sixteenth resonances were extremely weak. The harmonicity plots in Fig-

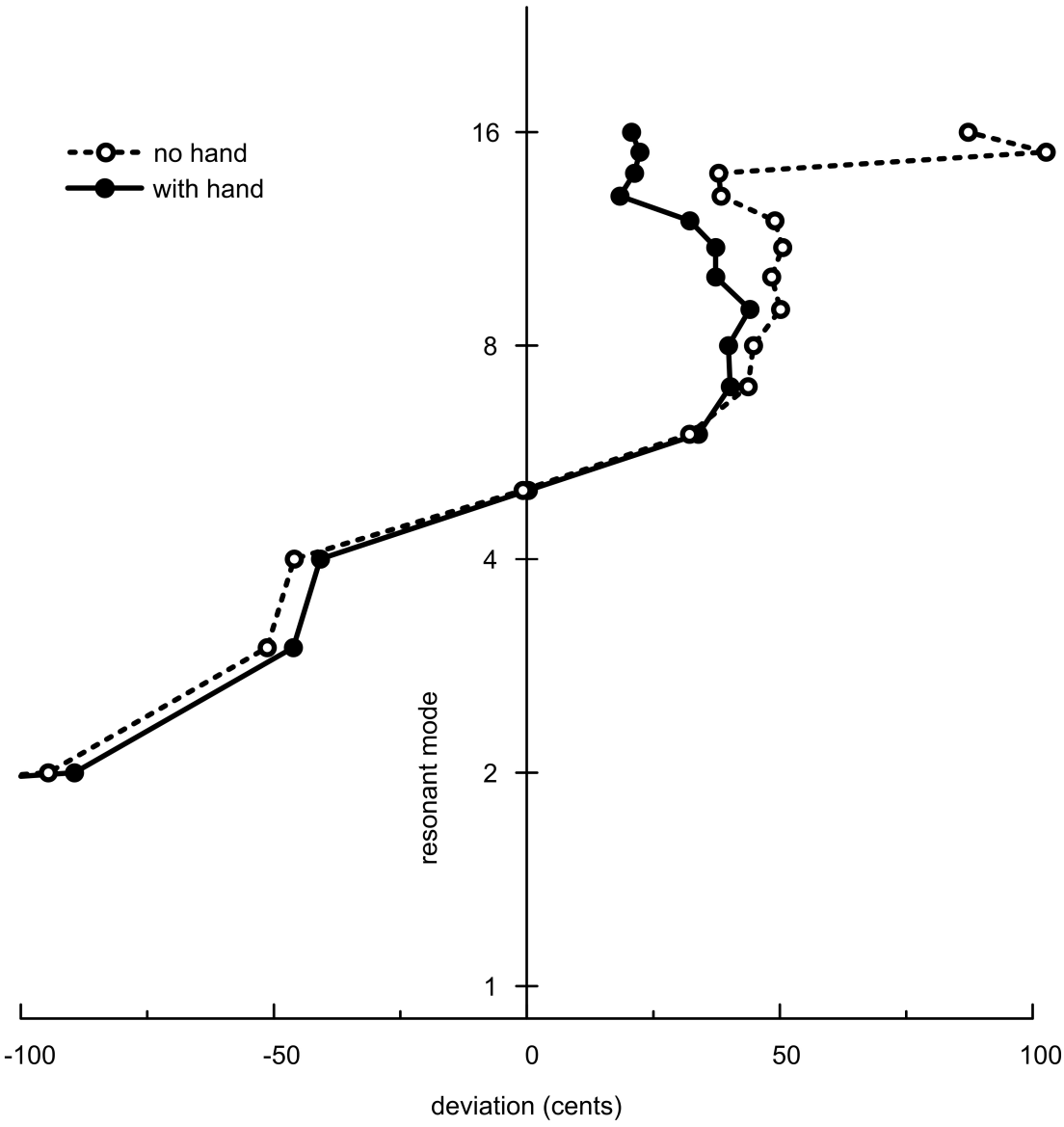


Figure 4.42: Harmonicity plot comparison for a horn by Saurle (A.KR.sk, Piz.005), from the early nineteenth century, measured with and without the hand in the bell.

ure 4.42 reveal the extent to which these modes are also noticeably sharp, and in this range there is no potential for extra support from upper resonances. The placement of the hand in the bell of the Saurle horn brings the sixteenth mode much more in line with the modes directly below. The harmonicity plots for the horn by Leichamschneider in Figure 4.43 show that the effect of the hand in the bell on the pitch of the resonances is much less pronounced.

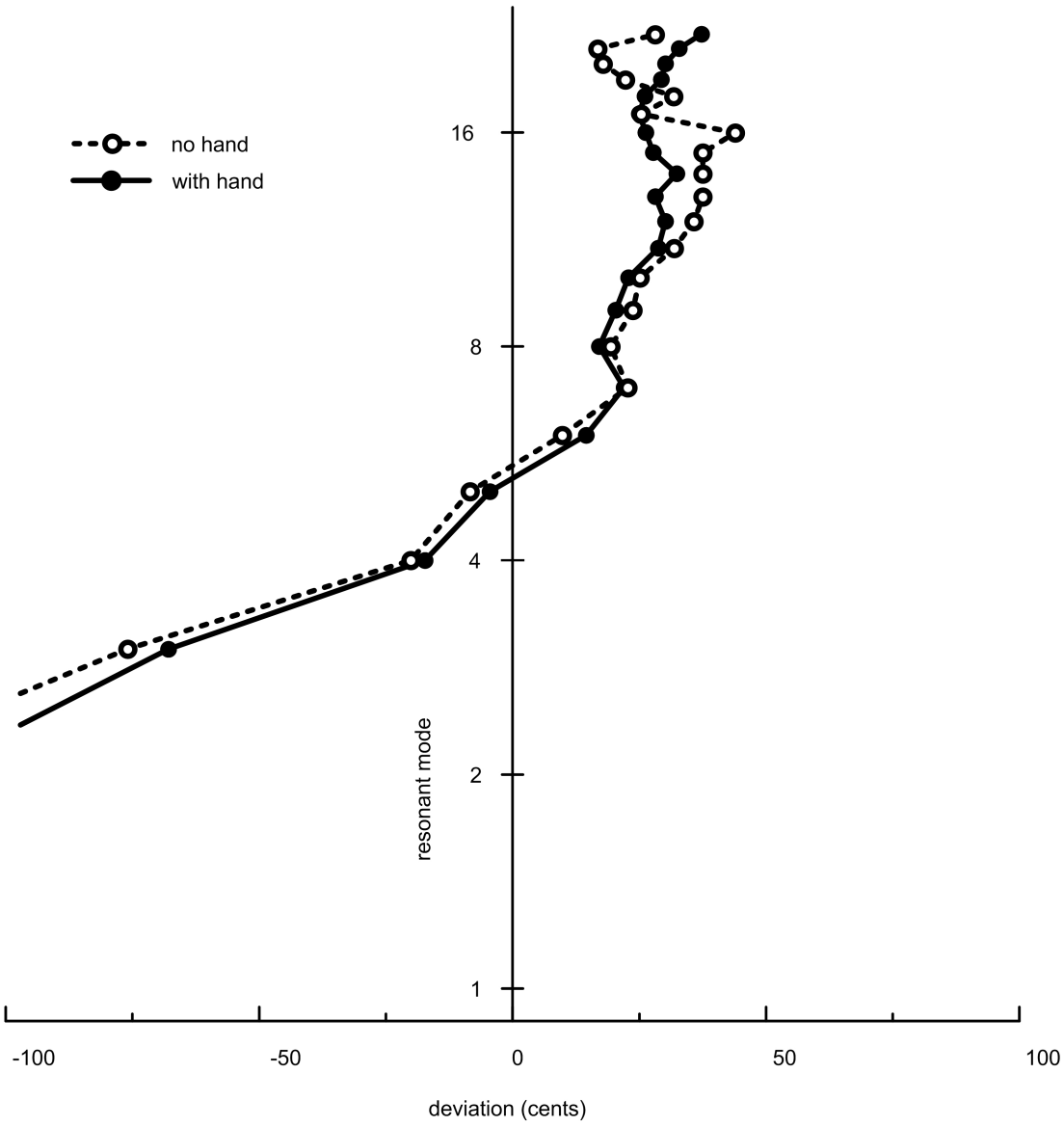


Figure 4.43: Harmonicity plot comparison for a horn by Leichamschneider (CH.B.hm, 1878.22.), dated 1718, measured with and without the hand in the bell.

In general, horns from the late eighteenth century displayed greatest divergence from harmonic alignment across modes four to sixteen than many of the horns from the first half of the century. The deviation was mostly characterised as increasing sharpness with increasing pitch, but became much less pronounced when the hand was positioned in the bell. This information may help to determine which instruments were intended to be played with some form of hand technique.

4.3.4 Q value ranking

The analysis presented in the previous two sections (4.3.2 and 4.3.3) highlighted the usefulness of the impedance curve for exploring the effect of the hand in the bell of the horn. Most of the examples involved comparing two instruments at a time, but it is also convenient to be able to compare many horns at a time. In this section, a systematic method of evaluation based on the ranking of Q values is proposed, in order to see more easily how different instruments compare.

It has already been suggested that analysis of individual resonances does not take into account the behaviour of the instrument as a whole, and particular resonances may vary independently as a result of small perturbations in the bore of the horn. As a very general trend, the horns included in this analysis all showed a similar pattern of variation in Q value across the range of the instrument. The typical shape of this variation can be seen in Figure 4.44, the Q values taken from the impedance curves of the horn by Saurle measured with and without the hand in the bell (Figure 4.40).

Generally the instruments displayed low Q values in the low register then the values increased towards approximately the eleventh resonance. For instruments of a later date within the dataset, as is the case here, the effect of the hand in the bell was found to increase the Q values in the high register. A steep decrease in the value of Q was common from about mode twelve and higher, and so initially the horns were ranked according to the average Q values of only modes twelve to sixteen with no hand in the bell; Tables 4.1, 4.2 and 4.3 below show a sample of the results.

From these tables it is apparent that instruments from the earlier part of the eighteenth century tend to have higher average values of Q across modes twelve to sixteen than those from later in the century, which would imply that the earlier horns are also easier to play in this range without the aid of the hand. Some of the instruments made more recently, including the modern double horn by Paxman (GB.E.chick, 2001.1), seem to have comparatively high values of Q across their complete set of resonances, and this may be due to the 'cleaner' internal condition of these instruments compared to older ones. Dust, dents, and corrosion on the

Instrument maker	Q value: average of modes 12–16	Fundamental frequency (Hz)	Date of manufacture
Buchschwinder	32	39.4	1742
Shaw	25	38.6	ca. 1790
Barth	21	38.8	ca. 1840

Table 4.1: Q value ranking (modern pitch E♭). Horns with frequencies between 38 and 40 Hz ranked in descending order of average Q value, modes 12-16 (no hand in the bell).

Instrument maker	Q value: average of modes 12–16	Fundamental frequency (Hz)	Date of manufacture
Meinl Baroque copy	30	43.8	n/a
Seraphinoff Baroque copy	29	43.8	n/a
anonymous	23	43.5	ca. 1790
Paxman modern	22	44.1	n/a
Werner	21	44.8	ca. 1770
Saurle	18	44.5	ca. 1790
Shaw	18	43.6	ca. 1790
Barth	17	44.0	ca. 1840

Table 4.2: Q value ranking (modern pitch F). Horns with frequencies between 43 and 45 Hz ranked in descending order of average Q value, modes 12-16 (no hand in the bell).

Instrument maker	Q value: average of modes 12–16	Fundamental frequency (Hz)	Date of manufacture
Eichentopf	31	45.4	1735
Werner	29	48.3	1735
Saurle	15	49.9	ca. 1790
Lausmann	15	46.2	ca. 1840
Shaw	12	49.4	ca. 1790
Barth	11	50.2	ca. 1840

Table 4.3: Q value ranking (modern pitch F♯/G). Horns with frequencies between 45 and 51 Hz ranked in descending order of average Q value, modes 12-16 (no hand in the bell).

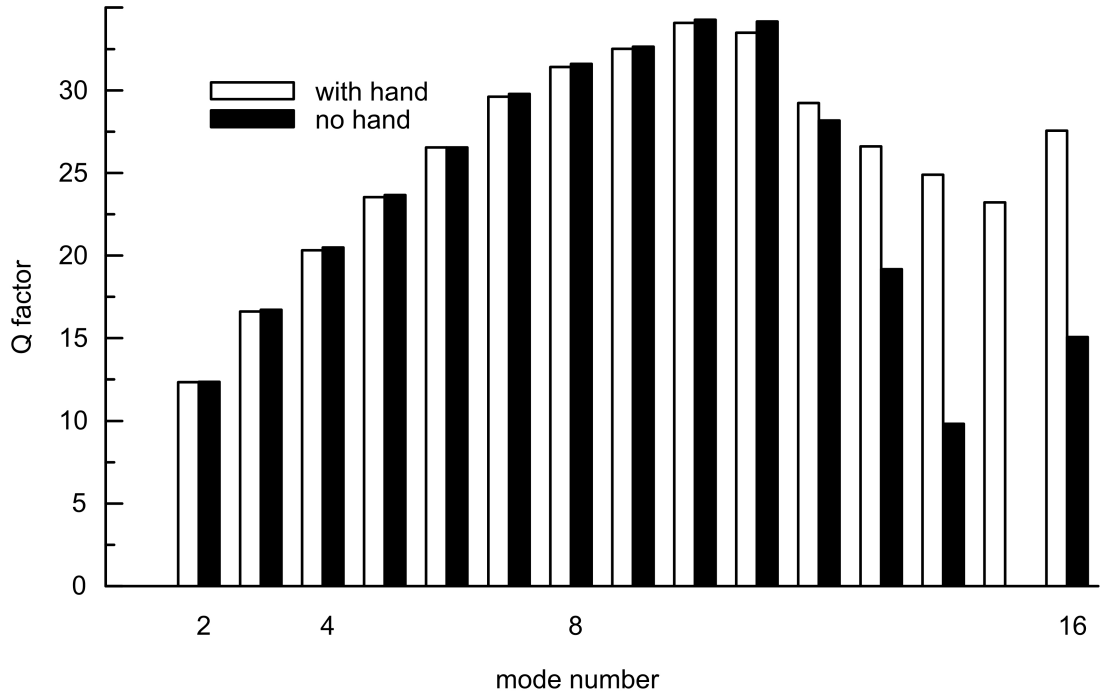


Figure 4.44: Q factor value comparison of a horn by Saurle (A.KR.sk, Piz.005), from the early nineteenth century, measured with and without the hand in the bell. The values for sixteen modes are shown, taken from the graphs in Figure 4.40.

inner walls of the tubing are thought to reduce the Q factor of brass instruments [Smithers *et al.*, 1986].

These findings seemed sufficiently interesting to warrant further investigation and so a slightly different approach to analysing the data was carried out; the average Q values of modes twelve to sixteen were compared to those immediately lower: modes eight to twelve. This gives a general indication of how quickly the Q values decrease (if at all) across this range. Tables 4.4 and 4.5 show the instruments ranked according to the difference between the average of modes eight to twelve, and modes twelve to sixteen.

A similar order to that of the previous tables can be seen, but with a few rearrangements; in general, the difference in Q value over the full range of modes eight to sixteen was more pronounced for the later than for the earlier instruments. In terms of how this relates to the response felt by the musician when playing the instruments, the greater the difference in Q value across this upper register, the less

Instrument maker	Q difference between: average of modes 8–12 and 12–16	Fundamental frequency (Hz)	Date of manufacture
anonymous	6	43.8	ca. 1790
Seraphinoff Baroque copy	8	43.8	n/a
Meinl Baroque copy	9	43.6	n/a
Werner	12	44.1	ca. 1770
Saurle	13	44.8	ca. 1790
Shaw	13	43.6	ca. 1790
Barth	13	44.5	ca. 1840
Paxman	15	44.0	n/a

Table 4.4: Q value comparison ranking (modern pitch F). Horns with frequencies between 43 and 45 Hz ranked in ascending order of Q difference between the average of modes 8-12 and 12-16 (no hand in the bell).

Instrument maker	Q difference between: average of modes 8–12 and 12–16	Fundamental frequency (Hz)	Date of manufacture
Eichentopf	4	45.4	1735
Werner	6	48.3	1735
Saurle	13	49.9	ca. 1790
Shaw	13	49.4	ca. 1790
Lausmann	18	46.2	ca. 1840
Barth	18	50.2	ca. 1840

Table 4.5: Q value comparison ranking (modern pitch $F^{\sharp}$/G). Horns with frequencies between 45 and 51 Hz ranked in ascending order of Q difference between the average of modes 8-12 and 12-16 (no hand in the bell).

secure the notes will feel to the player when ascending in this region. Concerning the instruments in Table 4.4, there appears to be a slight divide between those with a Q difference of 12 or 13, and those with a lower value of Q, perhaps an indication that the horns in the latter group might perform better without hand in the bell. On a few of the very early horns, modes twelve to sixteen even appeared stronger than the lower range of modes eight to twelve, suggesting greater security in this

very high register. Figure 4.45 shows photographs of two of the horns, one with low and one with high values of 'Q difference', from Table 4.5. Note the difference in the shape of the bells.

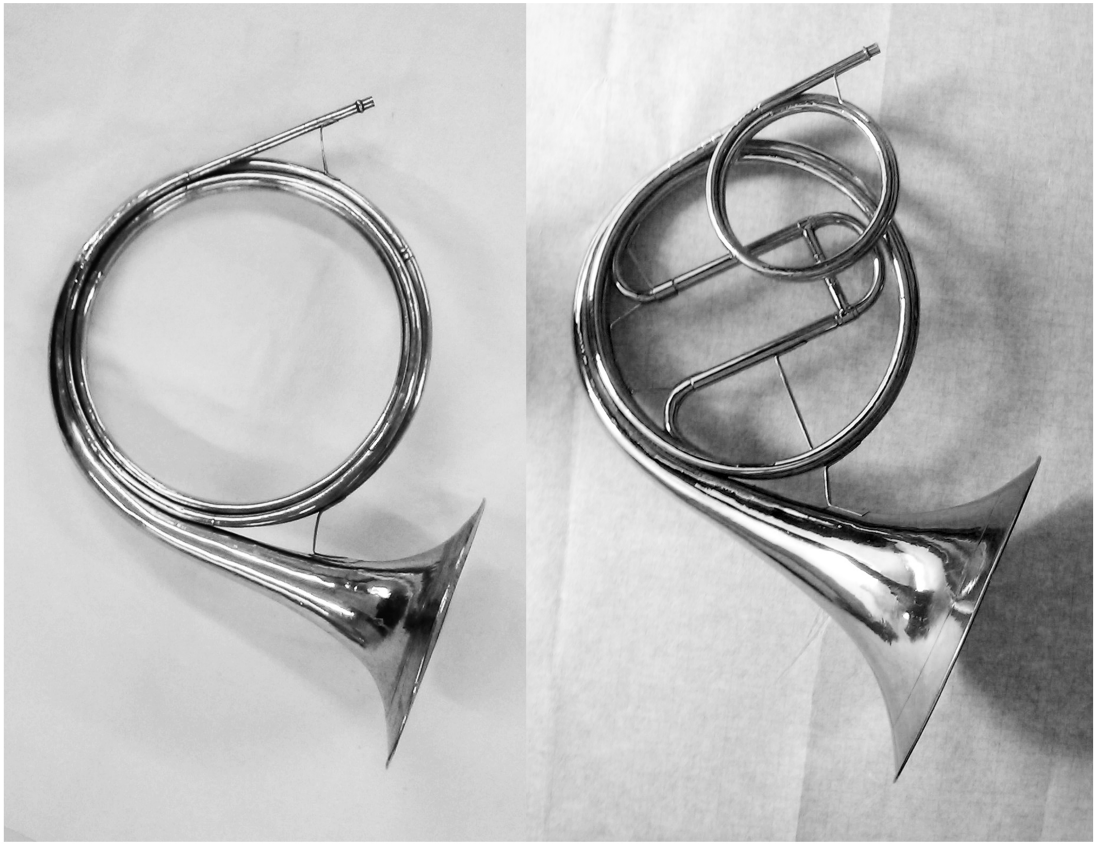


Figure 4.45: Photographs comparing a fixed pitch horn (left) by the maker Johann Heinrich Eichentopf, 1735 (CH.B.hm, 1980.2134.), to a crooked horn (right) by the maker Andreas Barth, mid-nineteenth century (A.KR.sk, Piz.003). The 'Q difference' for the horn by Eichentopf is 4 and for the horn by Barth, 18.

Many of the instruments in this data set were clearly made with hand technique in mind and so it is useful and important to also consider the effect on the Q values of placing the hand in the bell. The average of modes twelve to sixteen was compared with the hand in and out of the bell and the subsequent ranking based on this parameter produced results very similar to those in Tables 4.4 and 4.5. For example, instruments in which there was very little difference in the average Q values over modes eight to sixteen (from Tables 4.4 and 4.5) also showed very little difference in Q values between 'hand-in' and 'hand-out-of-the-bell' technique.

Again, this supports the theory that the design of horns from the early eighteenth century are more suited to 'hand out of the bell' technique than those made later in the century.

The instrument by Barth already mentioned, also showed the greatest increase in average Q after the introduction of the hand in the bell, an increase of about 10, whereas the average Q value for the horn by maker Johann Heinrich Eichentopf, dated 1725, rose by only 2. It is interesting to compare the bore profile of these two instruments, in particular that of the bell, in order to see the difference between a horn bell designed with hand technique in mind (the horn by Barth), and one most likely without (the horn by Eichentopf): a photograph of these two instruments can be found in Figure 4.45 and a bore profile comparison of the bell is shown in Figure 4.46.

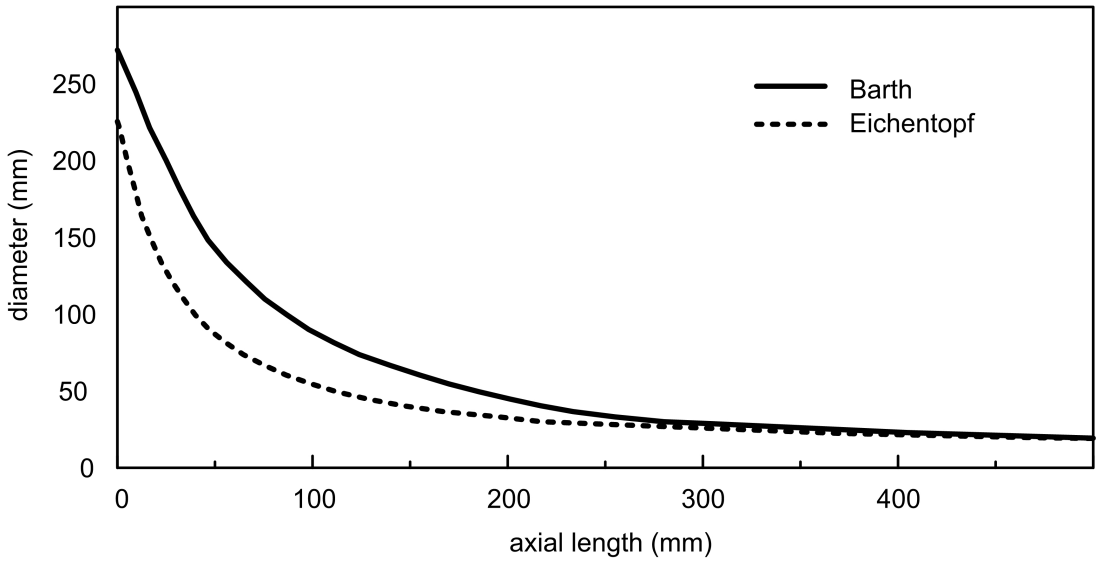


Figure 4.46: Bore profile comparison of two horns with about one hundred years separating their dates of manufacture. The earlier horn is by Eichentopf (CH.B.hm, 1980.2134.), dated 1735, and the later horn is by Barth (A.KR.sk, Piz.003), from the mid-nineteenth century.

4.3.5 Summary and further work

The effect of playing with the hand in or out of the bell is not only keenly felt by the player and apparent to the listener, but can be measured and analysed objectively from an acoustic point of view too, as demonstrated by these results.

The input impedance curve provided an indication of the unique acoustic response of each instrument, but among the horns examined, many shared similar shapes of curves; interesting groupings emerged between horns that use the crook-and-coupler system, and those which employ terminal crooks. The acoustic implications of the crook-and-coupler system seemed to indicate weaker resonances in the lower register, certainly at quiet dynamic levels, but stronger towards the middle register. Given that this system was strongly associated with horns from England, this is an interesting geographical characteristic which it would be worthwhile exploring further by expanding the data set.

Analysis of the impedance curves from late eighteenth- and early nineteenth-century horns, comparing the effect of the hand in the bell, revealed just how vital the hand is in increasing the strength of upper resonances for these instruments, particularly in the region of the sixteenth mode. Horns from earlier in the eighteenth century were generally found to have stronger upper resonances and the introduction of the hand in the bell had less of an acoustical impact.

The effect of the hand was also found to have a greater influence on the pitch of resonances on late eighteenth-century instruments, compared to those from earlier in the century. Harmonic alignment in the high register was more common amongst earlier instruments but the effect of the hand in the bell on later instruments resulted in increased harmonicity in the upper modes of these instruments too.

A more systematic analysis was achieved by investigating variation in Q values: horns from the early part of the eighteenth century showed the least decline in Q values over the range of modes eight to sixteen, and the introduction of the hand in the bell proved to have the least effect for these earlier instruments too. This is perhaps largely due to the shape of the bell profile. There appears to be

some correlation between date of manufacture and Q values, but measurements from more instruments are needed to explore geographical trends.

The results suggest that the evolution of horn design was a gradual process and that the transition to employing the hand in the bell also occurred gradually, with player technique and instrument design evolving simultaneously. One advantage of systematic analysis of instruments in this way is to observe general trends, but it can also prove useful for singling out horns with unusual or uncharacteristic acoustic response, or may even help to identify anonymous instruments. The potential for this will increase as more horns are examined.

4.4 Conclusions

The results from both embouchure and hand technique analysis have provided valuable additional insight into what technique might have been applied to which instruments.

Interpretation of acoustic impedance measurements was the key investigative tool in these experiments and was found to be particularly useful for analysing hand technique. This is because the effect of the hand in the bell on the acoustics of the horn could be seen clearly in the acoustic impedance results. Also, the measurements were objective and repeatable, and there was significant variation between the different instruments, allowing patterns to emerge from which conclusions could be drawn.

The effect of lipping however, is a more complex area, involving greater player influence in the coupling between the lips (concerning both technique and physical attributes of the embouchure) and instrument. As a result, measurements were found to be less repeatable than with the hand, and the differences between results were generally more subtle. There is still some uncertainty as to what makes a pitch on one brass instrument easier or more difficult to manipulate with the embouchure than on another, but these results suggest that harmonicity might play

an important role, and so further investigation into this area of acoustics would aid future research.

Involving human players in the experimental process was an important first step to exploring the link between player response and measured acoustic response. It would be useful in future investigations to consider a more objective method for examining lipping potential based on information provided by the input impedance curves. This would be helpful for assessing the qualities of one instrument in the context of many others. These results could then be used more easily in conjunction with the hand technique results to explore the link between horn design and playing technique.

Now that there are experimental results which suggest that some horns are more suited to lipping technique than others, it would also be interesting to compare these results with the typical range of notes required of horn players in different geographical regions and during different time periods. What was desirable of an instrument from the early baroque period (high clarino-style writing) may not have suited music from the classical era. Early brass instrument makers may not have had access to the acoustical measuring equipment we use today, but through trial and error, they became extremely skilful at designing and adapting the horn to the demands of each new generation of horn players.

Chapter 5

Design and ergonomics

Analysis of the design and ergonomics of eighteenth-century horns allows the issue of hand technique to be tackled from a more practical point of view, and is the main subject of this chapter. The introduction (5.1) discusses the ideas and observations which inspired this particular line of approach. Initial analysis of horn design was carried out by superimposing outlines of instruments and is discussed in Section 5.2. Next, specific horn dimensions are compared to see how these change over time (5.3) and then in Section 5.4, one particular measurement is investigated using techniques of ergonomic analysis to predict which horns are more suited to the use of the hand in the bell. Conclusions and further work are presented in the last section (5.5).

5.1 Introduction

Ergonomics is the scientific discipline concerned with investigating efficiency in design with reference to the human body. Much of the current research in this field is focused on improving the design of specific pieces of equipment for future application in the workplace. Of primary importance during the design process is the intended function of the object, thus 'form follows function' is a popular principle in this discipline. In the case of the early orchestral horn, controversy

reigns over whether or not hand technique was used to play instruments from certain periods and so it is interesting to turn the theory of ergonomics on its head in order to explore whether function (i.e. technique) can be predicted based on analysis of form. What can early orchestral horns tell us about how they might have been played?

5.1.1 Initial observations

Some horns are clearly more suited to hand technique than others. The method of playing the modern horn for example requires that the player place their right hand within the bell of the instrument in a position of support and only occasionally, and for special effect, is the hand required to be closed over the bell for the production of stopped notes or portamento effect. Although the hand is within comfortable reach of the bell in this scenario, it would be difficult and physically demanding to employ the nineteenth-century technique of often rapid hand movement in this region for any length of time due to the weight of the modern double (or triple) horn. The hand still retains some of its former role, as players often make subtle movements of the hand in the bell in order to fine-tune wayward notes. It also helps to soften the timbre of the instrument. Both of these effects are discussed in more detail in Chapter 4.

Stepping back in time a few hundred years, the weight of the horn was not such an issue: the orchestral horns from the classical era were valveless and as such, were considerably lighter, allowing the weight of the horn to be supported more easily with just one hand, leaving the other free to move comfortably within the bell. Figure 5.1 shows an image taken from the late nineteenth-century horn tutor by Henri Kling [c1900]. The diagram shows two views of the suggested open hand position where the hand sits within the bell, ready to close over the opening easily when required.

Hunting horns also have no valves and are relatively light compared to the modern horn, but the unwieldy nature of the large diameter coils on many examples of this type of instrument make hand technique impossible, or at least extremely difficult

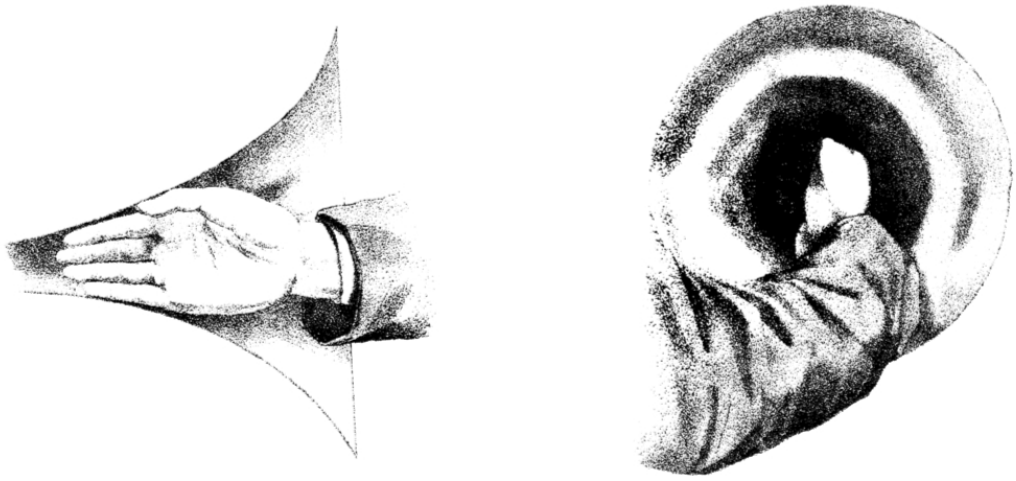


Figure 5.1: Drawing of a modern hand position in the horn bell, from two different angles. Image taken from the late nineteenth-century horn tutor by Henri Kling, *Horn Schule* [Kling, c1900].

and uncomfortable. A scaled modern horn and hunting horn are shown side by side in Figure 5.2 for comparison. The smaller and narrower bell shape of many early horns would also have made hand technique less of a comfortable option.

Figure 5.2: Scaled photograph showing the differences between a modern horn and a hunting horn.

It was also the case that hunting horns were often played on horseback and as such,

one hand would be needed to hold the reigns and control the horse. The other hand would have grasped this rather unwieldy instrument as securely as possible. There is an abundance of iconography showing hunting horns being played whilst on horseback. The image in Figure 5.3 shows a common hunting horn playing posture where the corpus of the instrument is supported by the whole of one arm. Some of the larger coiled instruments were made with a sufficiently wide corpus so

Figure 5.3: *Piquer de la vénerie de Naploéon III* by René Princeteau. A sketch of a horseback rider playing the horn [Monelle, 2006, jacket illustration].

that the whole instrument could be rested diagonally across the body when not in use for ease of carrying whilst riding. Even when not played on horseback, hunting horns were generally held in this manner (see image in Figure 2.2).

In the early eighteenth century, the size of the corpus was reduced as the horn came to be increasingly incorporated into orchestral performances, and in its more compact form, hand technique became a practical possibility. Two hundred years later and the practice of placing the hand in the bell of the instrument is now standard practice.

These three very different stages in the development of the horn cover a period of over three hundred years and help to highlight the link between form and function in horn design. The hunting horn, hand horn, and modern horn each require a different playing technique and as a result their respective designs reflect this. No other orchestral wind instrument requires the player to have their hand located in the bell of the instrument as the standard playing position. The horn differs in this respect largely because it developed into a form which made hand technique a viable possibility.

Eighteenth-century natural trumpeters encountered the same issues as contemporary horn players concerning wayward intonation and a limited range of notes, but the trumpet bell is not in a convenient location for the hand to be easily inserted. Attempts were made to design curved trumpets, called demilune trumpets, where the bell is slightly closer to the hand, but this design did not endure, perhaps partly because the role of the trumpet changed in the late eighteenth century and not long after this the valve was invented.

5.1.2 Focus of analysis

The large majority of instruments included in this survey are believed to have originated in either Germany or England, with a much smaller percentage coming from regions elsewhere. For this reason, the following discussion is focussed mainly on the comparison of characteristic design features from German and English horns. Details on all of the horns examined can be found in Appendix A.

During the first half of the eighteenth century, horn players in Germany, particularly those at the court of Dresden, appear to have been highly skilled musicians (see discussion of Hiebert's [1992] article in Section 2.2). Manuscripts from the court of Dresden dating from around this time show examples of technically, very demanding horn writing, including notes which might suggest that these horn players were perhaps some of the first to experiment with hand technique. English horn players on the other hand, are generally thought to have adopted hand technique at a later date, towards the latter part of the eighteenth century, therefore a comparison of horn design from both regions is of particular interest.

5.2 Outlines

Much of the physical aspect of playing the horn with the hand in the bell depends on the feature of horn design known as the wrap. This refers to the dimensions and layout of the coils of tubing. In order to compare the wrap of a number of different horns at the same time, a method of analysis was adopted whereby a scaled digital outline of each instrument is created, allowing the separate images from various horns to be superimposed and compared. This was found to be successful for carrying out initial observations because the natural horn has a relatively simple design, and features such as corpus diameter, bell shape, and mouthpipe angle are clearly defined.

The design of the horn today has become reasonably standardised; there is little variation in dimensions such as corpus diameter and bell diameter, with manufacturers mainly promoting options for more subtle differences in their instruments such as metal thickness, method of manufacture (spun or hammered bell) and the option to have a detachable bell. In the eighteenth century however, the horn was undergoing a period of great change and as a result there were many different shapes and sizes of instrument in use. Figure 5.4 shows an example of outlines from three very different eighteenth-century horns, including a large coiled hunting horn (left) by the maker Hieronymus Heinrich Franck, dated 1716 (D.N.gnm, W 3013), and at the other end of the scale, on the far right, a much

smaller instrument by the maker Friedrich Ehe (CH.B.hm, 1956.617.), dated from about the same period.

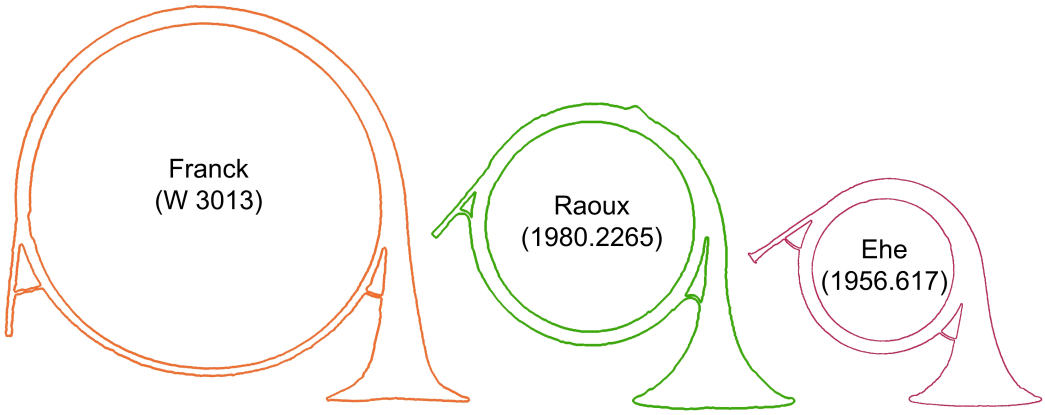


Figure 5.4: Outlines of three very different eighteenth-century horns: Franck dated 1716 (D.N.gnm, W 3013), Raoux from around the late eighteenth century (CH.B.hm, 1980.2265.), Ehe from around the early eighteenth century (CH.B.hm, 1956.617.).

These three instruments are all fixed pitch and have no 'moving' or 'moveable' parts, but as the horn developed, first crooks were added and then a tuning slide. The exact layout of features such as these are clearly visible on the outline image on the right in Figure 5.5. The horn in this example is by the maker Smith & Sons, from the late eighteenth century (GB.O.ub, 63) and both crook and tuning slide are visible in the outline. In contrast, a much simpler design of instrument from the early eighteenth century by instrument maker Bennet (GB.O.ub, 603) is shown on the left. Another useful aspect of this method of analysis is the ease with which consistency in manufacture within a workshop can be explored as will be discussed in Section 5.2.2.

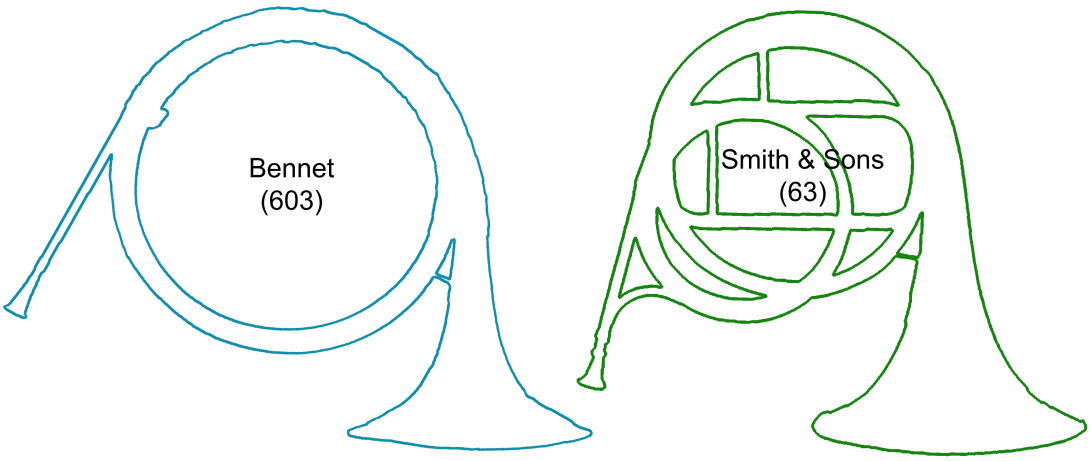


Figure 5.5: Outlines of two horns with very different wraps: Bennet from the early eighteenth century (GB.O.ub, 603) and Smith & Sons from the early nineteenth century (GB.O.ub, 63),

5.2.1 Method of analysis

The example outlines shown in Figures 5.4 and 5.5 were created by manipulating plan view photographs of horns, using image processing tools to define and scale the perimeter of the instrument. Care was taken whilst photographing the horns, to ensure that where possible the camera was positioned directly in line with the centre of, and parallel to the plane of the body of the corpus in order to minimise distortion. A test was also carried out to explore the extent of possible distortion and it was found to be insignificant for the purpose of this analysis. Details of this test can be found in Appendix D.

The photographs were then digitally manipulated using the photo editing software Adobe Photoshop in order to first extract the image from its surroundings (Figure 5.6), and then to highlight only the outline of the instrument (Figure 5.7). Physical measurements of the bell diameter were recorded for each horn and this allowed the instruments to be scaled in relation to each other, using the drawing

Figure 5.6: Photograph of a horn by Smith & Sons (GB.O.ub, 63) which has been digitally manipulated in order to extract the image from its surroundings.

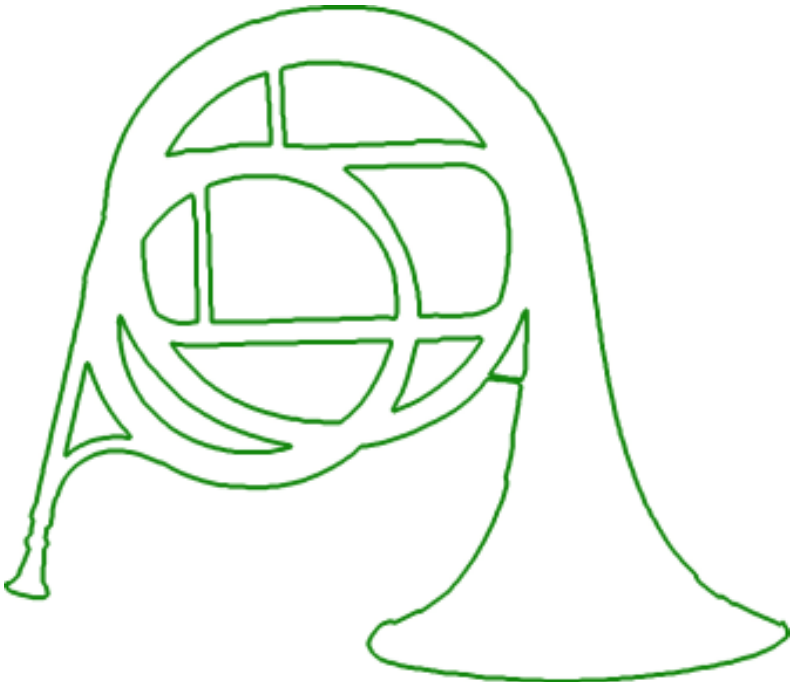


Figure 5.7: Outline of a horn by Smith & Sons (GB.O.ub, 63) which has been edited to show the midline of the border around the image from Figure 5.6.

programme, Microsoft Visio.

5.2.2 Results and discussion

Horns made today are not only much more standardised in design when compared to eighteenth-century instruments, but the manufacturing process is also much more consistent, with many instruments made predominantly from machined parts. It is also the case that some modern manufacturers concentrate on producing only one part of the horn such as the bell, or the valve section, and will supply many different companies worldwide. Even amongst models of horn which are 'hand made', the level of consistency is high. Using the method described in Section 5.2.1 of comparing the outlines of instruments, it was interesting to explore the extent of variation in manufacture and design of eighteenth-century horns made within the same workshop or by the same instrument maker.

Amongst the many horns examined, there were several groups of instruments associated with the same maker, including five horns by Nicholas Winkings, made in England around the middle of the eighteenth century. Three of these horns are pitched in D and therefore suitable for comparison. Superimposed outlines of these instruments can be seen in Figure 5.8. The positioning of the images is based on alignment of the centre of each corpus, keeping the angle of the three mouthpipes close to parallel. In this comparison, variation occurs in a number of areas; the corpus diameters are slightly different, the length of the mouthpipes as they extend from the corpus differ, and the angle between the axes of the mouthpipe and that of the bell varies.

Another example of variation in manufacture within a London workshop can be found in the work of the instrument maker Christopher Hofmaster. He was producing horns around the same time as Winkings (mid eighteenth century) but of a slightly different design. Whereas the Winkings horns demonstrate a fixed pitch model, the Hofmaster instruments were made to be played with crooks and couplers. Figure 5.9 shows a comparison of three instruments by the maker Hofmaster. The same method of alignment was used here as on the previous example, but it

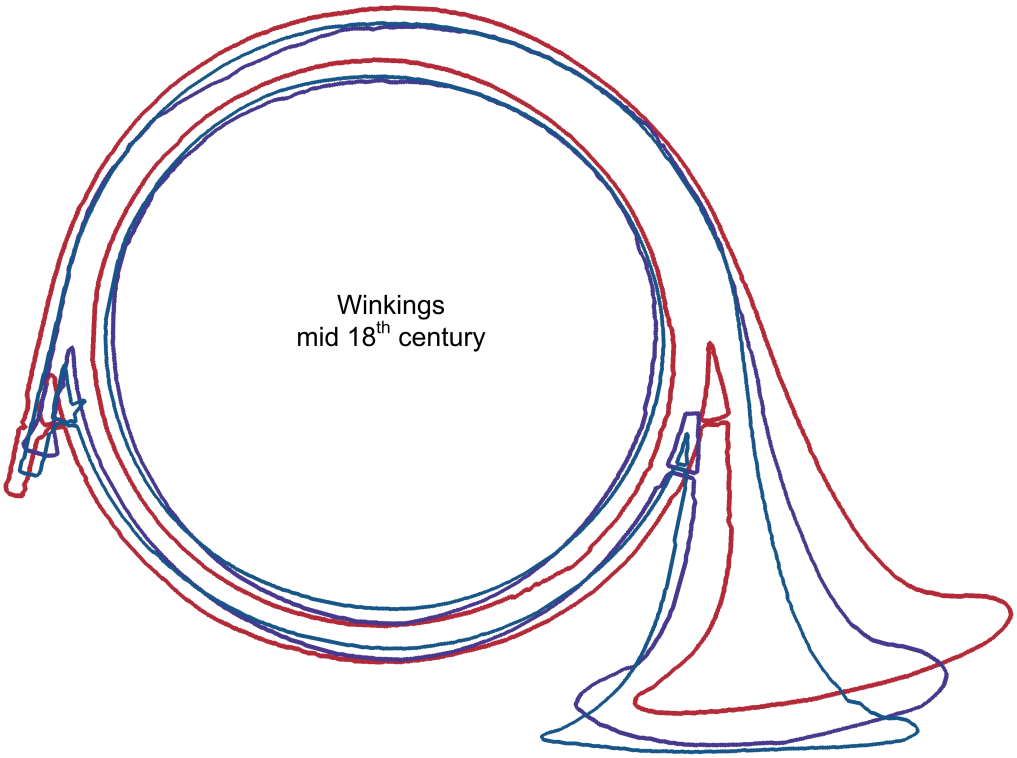


Figure 5.8: Outline comparison is between three horns by the maker Winkings (GB.E.u, 2492) (GB.E.u, 2493) (GB.O.ub, 604) all pitched in D. Slight variation is apparent concerning the corpus diameters and the angles between mouthpipe and bell.

should be noted that in one of the outlines, the instrument has a different crook combination compared to the other two. The variation amongst these three horns is not quite as pronounced as in the Winkings comparison. The corpus diameters are very similar however there is still some discrepancy concerning the distance and angle between the mouthpipe and the bell.

A possible reason which may contribute to the discrepancy between the Winkings horns could be damage or subsequent repair work on the instruments. This is a possibility which has to be considered when examining any historic instrument. In the case of horns, it was not uncommon for mouthpipes to have been adapted at some stage in their history, to make the instrument either shorter or longer

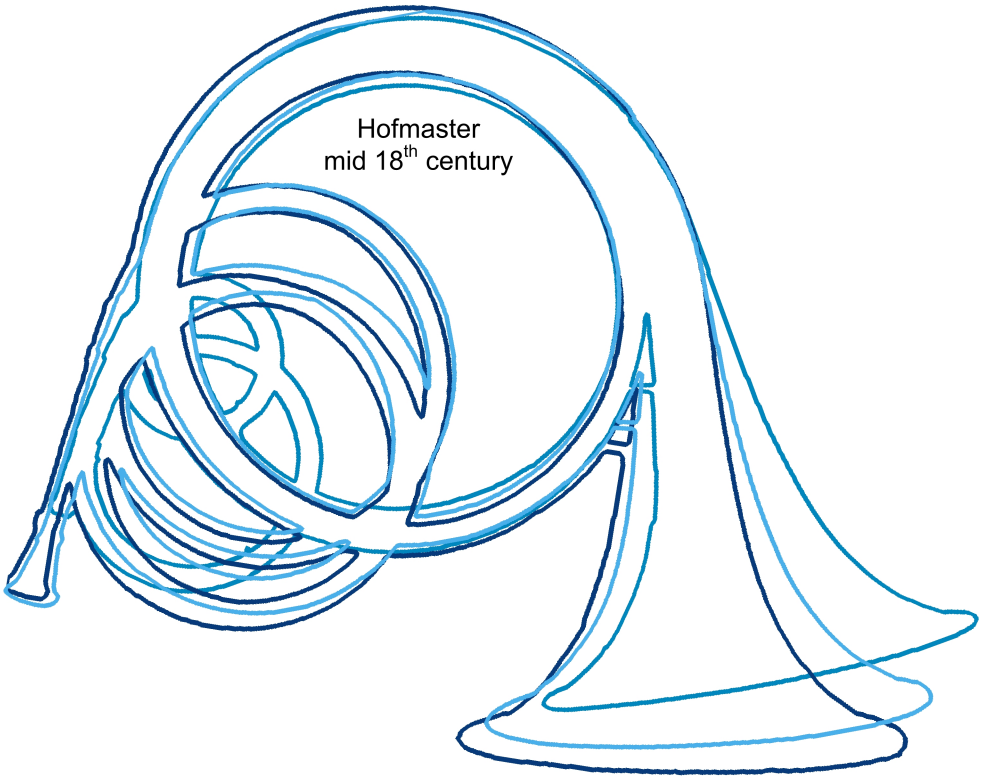


Figure 5.9: Outline comparison is between three horns by the maker Hofmaster (GB.E.u, 3297) (GB.O.ub, 606) (GB.O.ub, 607). Slight variation is apparent concerning the angles between mouthpipe and bell.

so that it could be played at a slightly different pitch. The physical condition of the Winkings horn group is generally not as good as the Hofmaster instruments. Another possibility might be that the horns were not crafted by the same maker; popular manufacturers might have hired craftsmen to make instruments under the same name and in the same workshop but this might have introduced greater variability.

Some instruments from the eighteenth century were found to be remarkably similar, showing high levels of consistency. The superimposed outlines in Figure 5.10

show a pair of anonymous horns, one right and one left handed. These instruments are thought to be of English origin, dated from around the late eighteenth century or early nineteenth century. In terms of the shape of their outlines, they appear to be almost identical. This shows that from as early as the turn of the century, horn makers were able to build instruments to very precise specifications and ensure repeatability within their workshops.

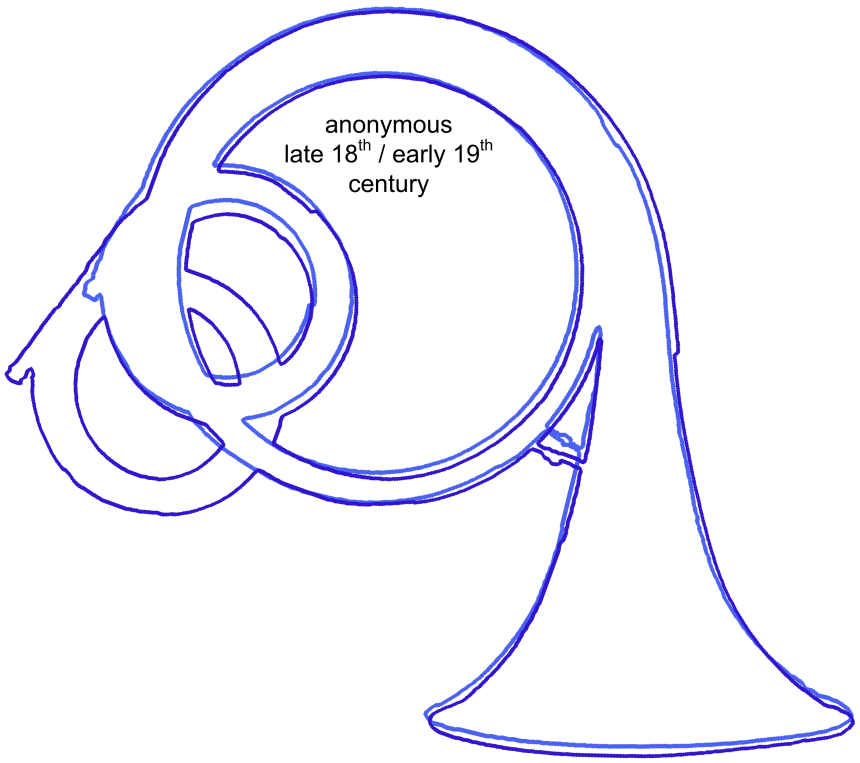


Figure 5.10: Outline comparison is between two horns by an anonymous maker (GB.E.u, 2887) (GB.E.u, 2888). These two horns are almost identical in terms of wrap, corpus diameter and bell profile.

5.2.3 Summary

As an initial method for analysing the wrap of early horns, comparison of outline profiles proved to be useful, particularly when investigating consistency in manufacture within various instrument workshops. A major advantage of this method is that not only can several instruments be analysed at the same time, but several aspects of their design can also be examined in combination, allowing the instruments to be considered as a whole. Another benefit of this technique is that a large amount of data can prepared for analysis in this way; all that is required is to take a photograph and a bell diameter measurement, and these two procedures take very little time. Many musical instrument collections now provide this information online for anyone to access.

Outline comparison is limited however, in that the analysis can become overcrowded when too many instruments are superimposed together and visual distinction between the different instruments becomes more difficult. In order to compare the design of many horns together, a more abstract approach is required where the variation of each dimension is examined separately. This is the approach described subsequently in Section 5.3.

5.3 Dimensions

The comparison of selected dimensions from a large dataset of early horn measurements allows a more objective analysis of variation in horn design over time to be carried out. With the introduction of the horn into the orchestra and the subsequent adoption of hand technique, the design of the horn changed to meet new practical requirements. For example, the new method of playing meant that the bell now needed to be large enough to accommodate the hand, it also needed to be within comfortable reach of the hand, and the coiled tubing of the corpus no longer needed to be large enough to loop round the body as was sometimes the case with hunting horns. Thus the main dimensions intrinsically linked to hand technique include the bell diameter, the distance from the mouthpiece to the

bell, and the corpus diameter. These measurements are the subject of analysis in this section and are discussed with reference to player technique and geographical trends over time.

The image in Figure 5.11 shows the three physical dimensions marked on a photograph of a horn: bell diameter (green arrow); distance from mouthpiece to bell (red arrow) and corpus diameter (blue arrow). It should be noted that the length

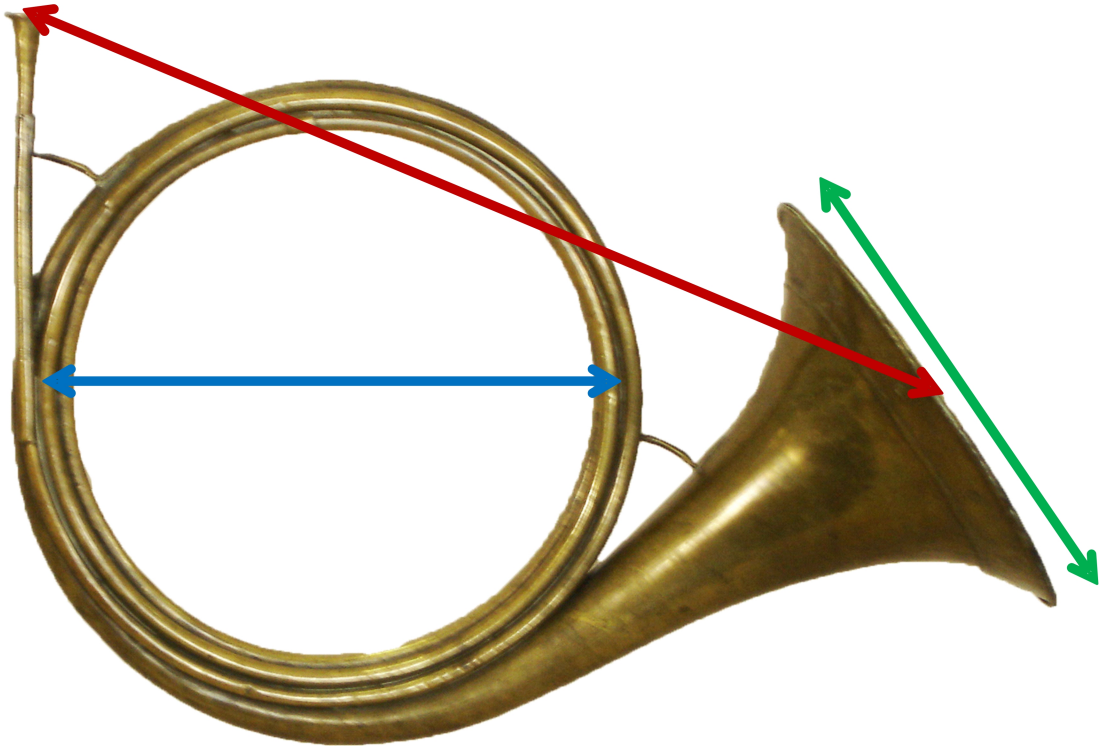


Figure 5.11: Image of a horn showing three dimensions important for ergonomic analysis: bell diameter (green), distance from mouthpiece to bell (red), and corpus diameter (blue).

of the red arrow spans from the mouthpiece to a mid-point on the bell. This mid-point is located at the centre of the plane of the bell and it was chosen as a very approximate indication of where the hand might lie of it were to be used within the bell of the horn. In reality, it is likely that the position of the hand varied from player to player, region to region, and over time. However, in order to carry out a systematic analysis and to limit the number of variables, this fixed position was chosen as a suitable reference point. Even horns that were clearly never intended to

be played with hand technique, such as large coiled hunting horns, were subjected to the same analysis for the sake of comparison.

It was important to include large coiled hunting horns in this research because consideration of the function of the hand in the bell played no part in the design of this type of instrument. Other factors such as portability and tone quality may have been more influential in the design process of the hunting horn. Inclusion of the hunting horn data does however raise some challenges when plotted alongside the other instruments, and this concerns the dual nature of the development of the horn in the eighteenth century. This point is illustrated clearly in the two examples shown in Figure 5.12.

These two horns were clearly designed to very different specifications, yet they came from the same workshop, that of Friedrich Ehe, and are dated from around the same period, *c*1720. The smaller horn (D.N.gnm, MIR 74) may have been intended as one of the first orchestral horns, whereas the style of design on the larger horn (D.N.gnm, MIR 72) implies its use in the hunt. The hunting horn did not immediately decline from use after inspiring the development of the orchestral horn, instead the two instruments coexisted, each fulfilling a different demand, with both instruments in frequent use throughout the eighteenth century.

Figure 5.12: Photographs showing two horns from the workshop of Friedrich Ehe, both made *c*1720, but with different designs. Top: Ehe (D.N.gnm, MIR 74). Bottom: Ehe (D.N.gnm, MIR 72)

5.3.1 Measurement procedure

To measure the bell diameter, the maximum width was recorded at several different places and where this varied, an average was taken. The corpus measurement was calculated based on an average of the maximum and minimum coil diameters, and is intended as an approximation.

It was difficult to take a physical measurement of the length from the mouthpiece to the central point in the plane of the bell and so initially this was calculated based on the measurements of two related dimensions shown in Figure 5.13. These are,

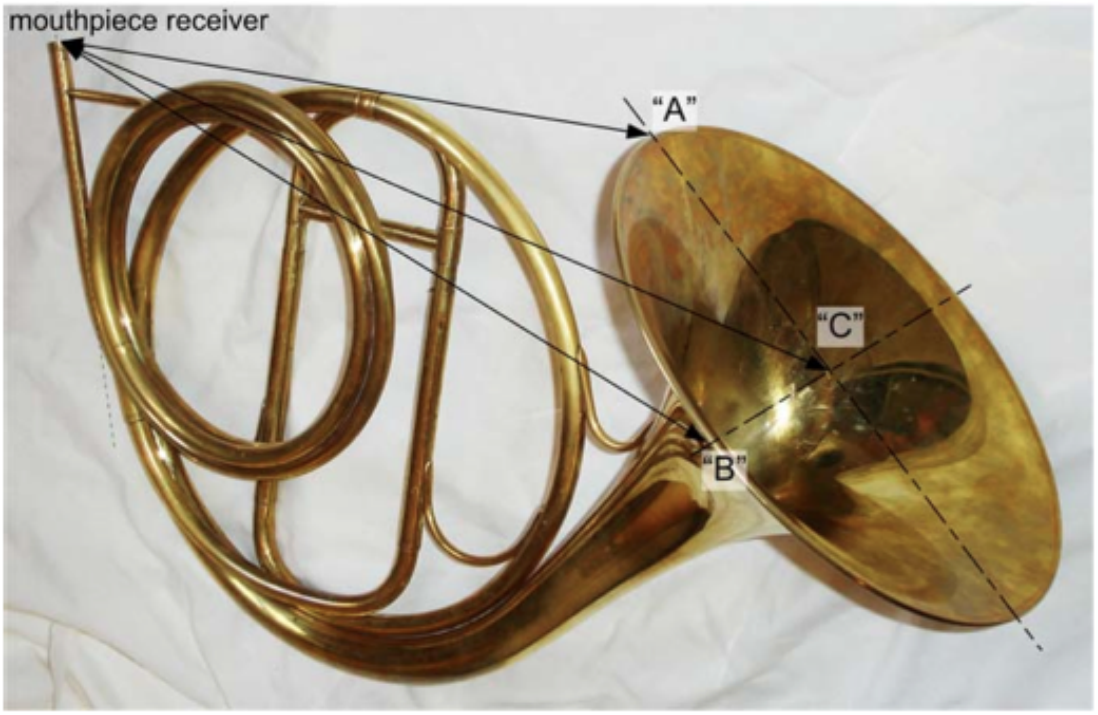


Figure 5.13: Image of a horn showing two dimensions from the mouthpiece receiver to point A and B on the bell, which were measured in order to calculate the length from the mouthpiece receiver to point C on the bell.

the length from the mouthpiece to point 'A' on the bell, and from the mouthpiece to point 'B' on the bell. The location of 'A' can be described as the point on the bell rim that lies in the plane of the corpus and is nearest to the mouthpiece receiver. Location 'B' is the point on the circumference of the bell rim, 90° from point 'A'. For horns intended to be played with crooks, measurements were only carried out

on instruments which could be fitted with an appropriate F crook combination. The desired length (mouthpiece to point 'C' shown on Figure 5.13), could then be calculated using Pythagoras' Theorem.

The method described for calculating the distance from the mouthpiece to the central point in the plane of the bell, proved to be problematic. Physical measurements to the points 'A' and 'B' shown on the bell in Figure 5.13 were difficult to record accurately. Also, instruments which were missing crooks could not be measured and so were initially not included in the data set. For these reasons, an alternative method was adopted whereby the Pythagorean calculation was carried out based on measurements taken from a maximum size, hard copy of a photograph of a horn instead, the results scaled accordingly. An example of a sample photograph with dimensions plotted is shown in Figure 5.14.

The centre point in the plane of the bell can now be defined much more precisely and in the case of horns missing crooks, estimations were made based on a horn crooked in F with a mouthpiece fitted. This alternative method was found to produce more accurate results even when taking into account photographic distortion. As mentioned previously, the extent of potential image distortion was explored in a test described in Appendix D, but was found to be of negligible significance for the purpose of this investigation. The success of the photographic analysis meant that the dataset could be expanded to include carefully chosen photographs of instruments from catalogues of musical instrument collections, where bell diameter measurements are also included.

The dimensions were then plotted against date of manufacture in order to show how horn design has varied over time. A number of horns measured have not yet been dated accurately and so in cases where the potential period of manufacture is too broad, the horns have mostly been omitted in order to maintain as clear a historical perspective as possible. Where the date of manufacture has been predicted, this has been rounded to the nearest decade based mainly on information provided in the *New Langwill Index* [Waterhouse, 1993]. It is to be noted therefore, that the results presented in the following graphs are indicative only of general trends.

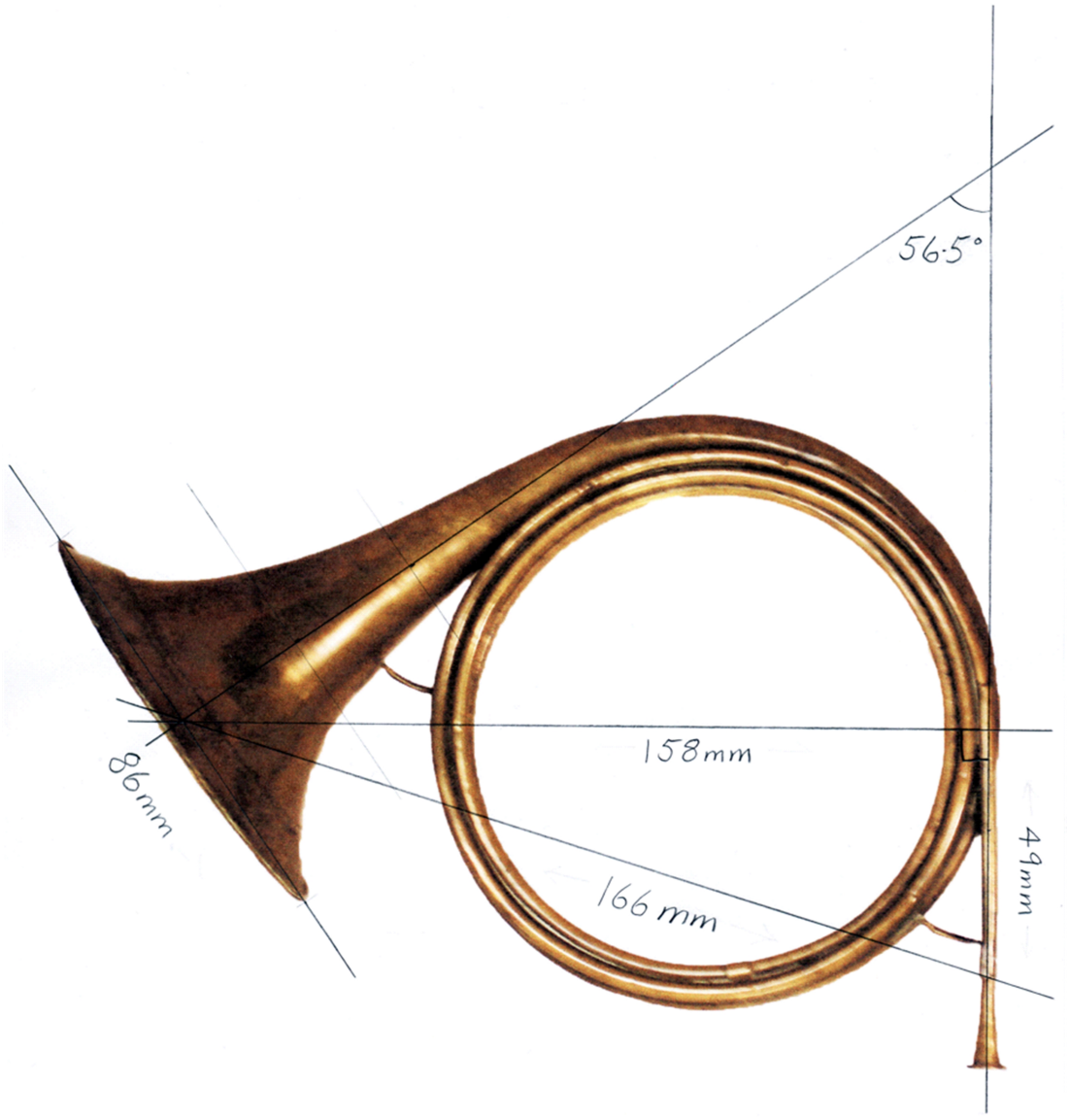


Figure 5.14: Image of a horn with dimensions plotted in order to calculate the angle between the mouthpipe and the bell, and also the length from the mouthpiece receiver to the mid point on the bell.

5.3.2 Bell diameter

The variation in bell diameter over time can be seen in the scatter graph in Figure 5.15. A positive correlation between bell diameter and date of manufacture is evident although not particularly strong. The overall trend shows a general

increase in bell diameter with time.

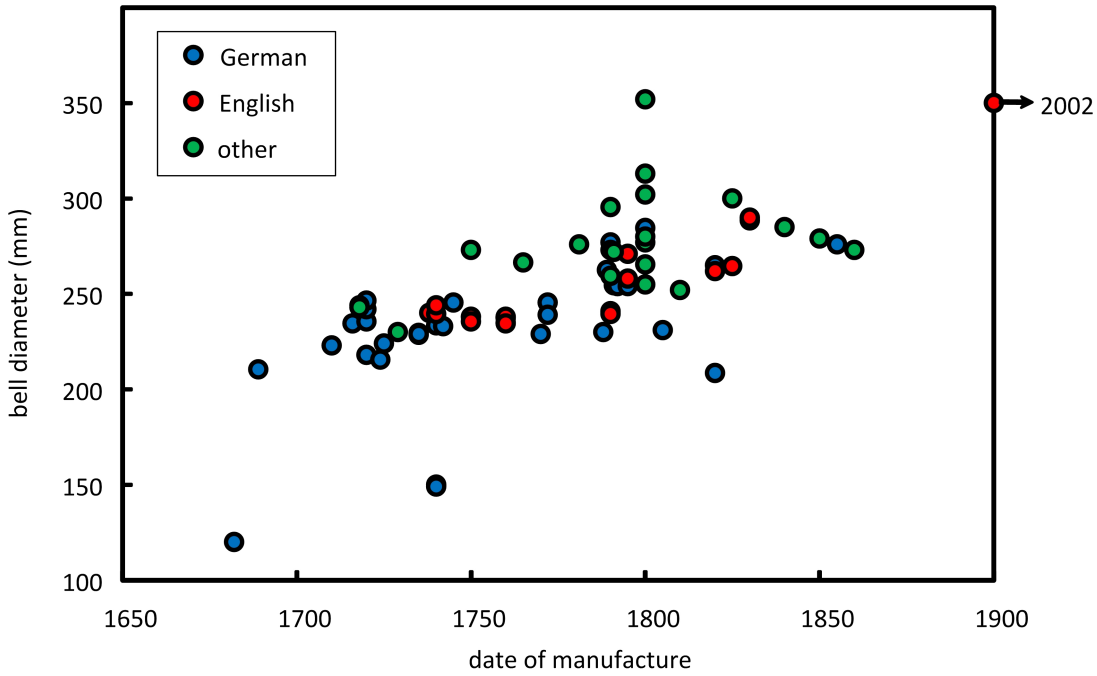


Figure 5.15: A scatter graph showing the variation in bell diameter over time. Horns are coloured according to geographic location and an example of a typical modern horn has also been included in the far right of the graph.

Towards the latter part of the eighteenth century there appears to be much less uniformity of bell diameter, possibly due to the fact that both hunting horns and orchestral horns are included in this survey and by this stage in the development of the horn, many aspects of the design of these two types had diverged significantly. It might also perhaps indicate that new technology became available in the latter part of the eighteenth century allowing wider diameter bells to be made more easily. This is merely a supposition however, and more data and further investigation is needed to substantiate this idea.

Modern instruments have a relatively large bell diameter in comparison with eighteenth-century horns as can be seen by the red data point included on the far right of this graph. This point represents the bell diameter of a common model of horn by the instrument manufacturer Paxman (GB.E.chick, 2001.1). A similar reference point has been included on all of the following graphs.

5.3.3 Corpus diameter

The variation in corpus diameter over time can be seen in the scatter graph in Figure 5.16. A trend is apparent revealing a negative correlation overall, but much

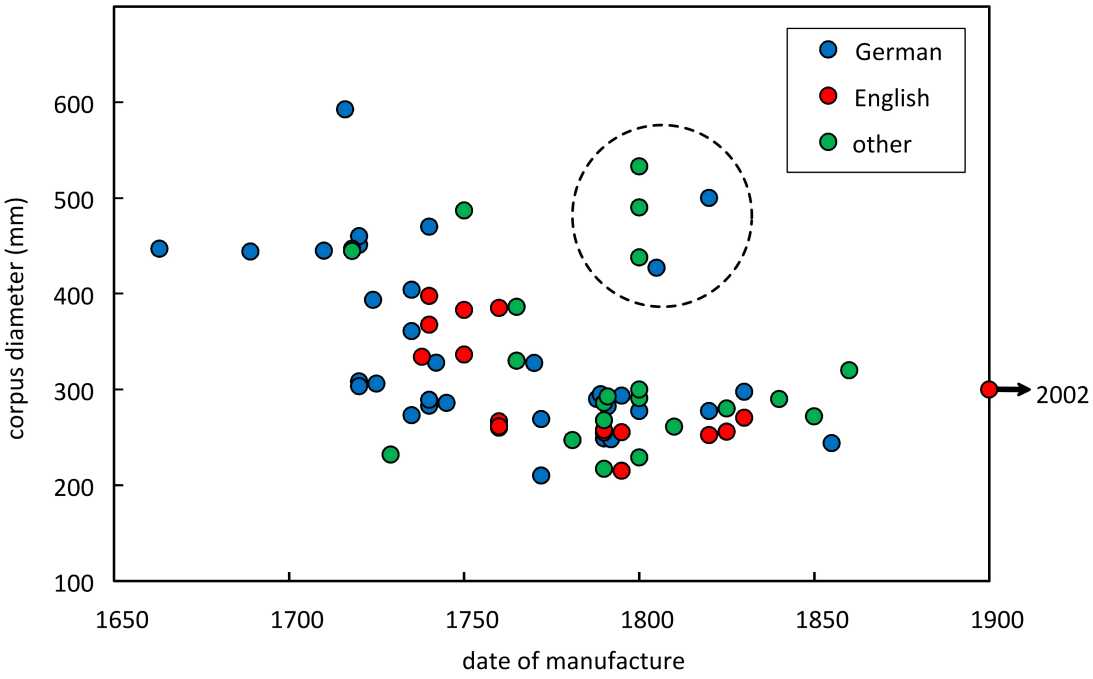


Figure 5.16: A scatter graph showing the variation in corpus diameter over time. Horns are coloured according to geographic location and an example of a typical modern horn has also been included in the far right of the graph. The points within the dashed circle represent a group of late period hunting horns.

like the previous graph, there is a great deal of spread amongst the data points, largely as a result of including hunting horns alongside orchestral horns. In this graph however, the two divergent styles of instrument design can be seen quite clearly towards the end of the eighteenth century. The five data points enclosed in a dashed circle represent hunting horns and they form a distinct group on their own. Initially some hunting horns were made with a large corpus so that the instrument could be supported across the body for ease of transport on horseback and this became a feature of hunting horn design.

As an orchestral instrument, there was no need to have such a large corpus and so the horn soon became more tightly wound. This change is apparent from the

shape of the scatter in Figure 5.16. In the first half of the eighteenth century, horns were being made with largely varying corpus sizes but towards the end of the eighteenth century the corpus diameter appears to have levelled off to a width of approximately 250-300 mm, very similar to the size of a modern horn corpus which is about 300 mm on average (see the modern horn point on the far right).

5.3.4 Bell location

The scatter graph in Figure 5.17 shows how the distance from the mouthpiece to the bell of the horn has varied over time. For details of the exact length this refers

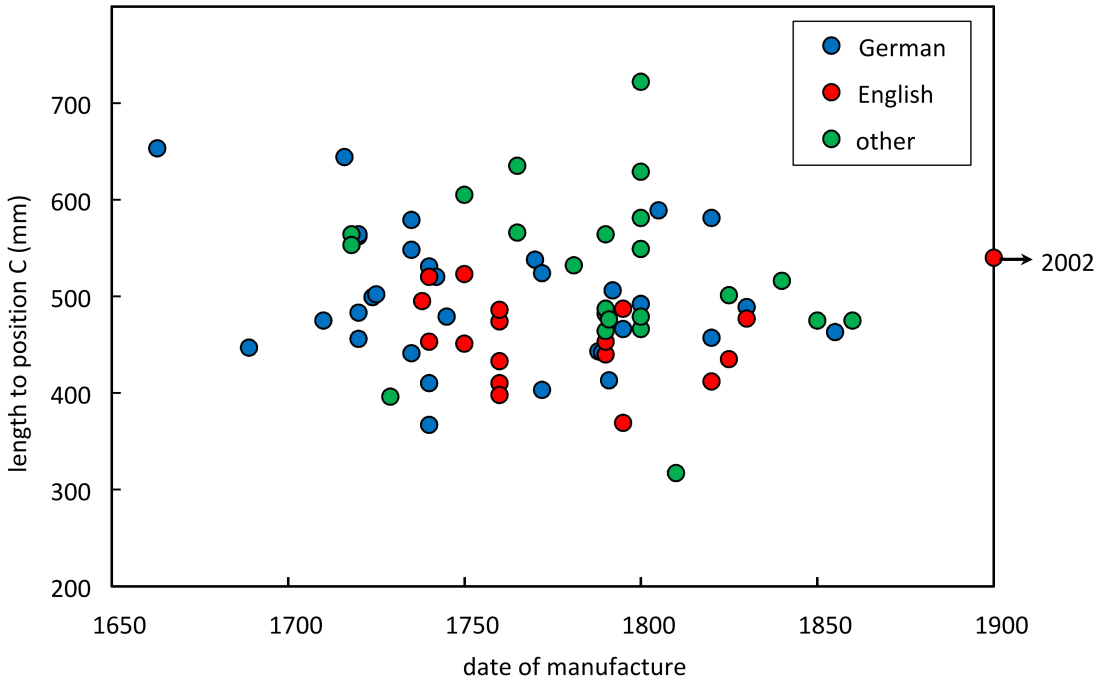


Figure 5.17: A scatter graph showing variation in the distance from mouthpiece to bell over time. Horns are coloured according to geographic location and an example of a typical modern horn has also been included in the far right of the graph.

to, see Figure 5.13. Of all the dimensions examined, it was initially thought that this dimension would provide the greatest insight into which horns were intended for use with the hand in the bell. From an ergonomic perspective, the bell needs to be located at a suitable distance from the mouthpiece for the hand to be within easy reach. The results displayed in Figure 5.17 however, show no apparent trend.

The only noticeable feature of this graph concerns a cluster of points representing instruments from the late eighteenth century. The design preference at this time appears to have been a mouthpiece-to-mid-bell length of about 400-500 mm, slightly less than the distance on a modern horn. A possible reason for such a dense cluster at this point, is that many of the horns measured were from the late 1700s and fewer from the nineteenth century. It is possible that if more nineteenth-century instruments had been included in the survey, the points might have been seen to converge.

5.3.5 Summary

Generally these graphs would benefit from an expansion of the dataset to include more nineteenth-century instruments and also perhaps greater distinction between orchestral- and hunting-type horns. Nevertheless, trends were apparent in the graphs showing variation in bell and corpus diameter over time. These trends were consistent with the new demands on the horn as a result of hand technique, i.e. a larger bell to accommodate the hand more comfortably and a more compact instrument for ease of use in the concert hall.

The final graph showing variation in the distance from the mouthpiece to the bell was not as revealing as might have been expected, but provided the incentive for the next stage of the investigation; these graphs provide a very abstract view of horn design and development, and as such they can be challenging to interpret in the context of player technique. Subtle and more complex changes in horn design are likely to be missed and so a more integrated approach is needed. The next section (5.4) examines the instrument as a whole and its relation to the player.

5.4 Ergonomics

Some horns are more comfortable to play with the hand in the bell than others, but defining which instruments, to what extent, and why, is more difficult. Unlike the

previous analysis of specific key horn dimensions, it is not easy to assign a value to the ease of ergonomic comfort in horn playing. The study of horn ergonomics is a complex area involving variables such as the weight and dimensions of the horn, and the physique and technique of the player. It is therefore vital to consider both instrument and player in this investigation.

The first important question: *why* are some horns more comfortable to play with the hand in the bell than others? General feedback from players when asked this question is the feeling that there is an optimum position concerning the distance of each hand relative to the body when supporting the horn in this manner. A review of the published literature concerning ergonomics and horn playing revealed this to be an untapped avenue for research. Although it was apparent that ergonomic analysis had not yet been applied directly to historic horn playing, or indeed any form of horn playing, there has been some interesting research looking at a 'normal working area' in terms of the comfortable reach of the arms, and so this formed the starting point for the following investigation.

5.4.1 Theory

There has been much written about ergonomic design in the workplace, with a particular emphasis on the manufacturing industries where workers are required to carry out physically demanding tasks which often pose potential health risks [Chaffin *et al.*, 2006; Khan, 2010; Stock, 2007]. Research into this area has mainly been carried out with a view to assessing the impact of certain tasks on the human body, and then subsequently on improving the ergonomic design of tools and equipment used by workers in order to minimise strain.

Studies concerning the ergonomic design of musical instruments are scarce, however similar theories to those discussed in the context of ergonomic design in the industrial workplace can be applied to the task of playing the horn. The main difference is the motivation for the research: the following investigation does not look to improve the design of the horn for the future, but instead explores possible motivation for aspects of early horn design which may be linked to player technique

in the past.

The first task was to establish what a comfortable playing position with hand in the bell might be. Playing the horn is a relatively static task: the instrument is held in one position for varying lengths of time and as such, physical demands are mainly placed on the arms of the player. The position of the arms in relation to the body is one of the key factors which determines how comfortable a person is when carrying out a specific task, such as typing at a keyboard.

Many ergonomic diagrams have been created to demonstrate comfortable working areas for the hands and arms. These diagrams are mainly aimed at those designing office workstations so that the optimum place can be found for various items of office furniture and equipment. The static nature of horn playing where the horn is held out in front, is not entirely different from the static nature of office work and so it is proposed that these diagrams might also prove useful for determining a comfortable horn playing position.

Two of the first scholars to carry out experiments in this area in order to define a comfortable working area for the arms, were Squires [1956] and Barnes [1968]. The diagram in Figure 5.18 shows the results from their findings. The dimensions of the normal working area for both arms have been plotted in the horizontal plane, according to the two different authors; Squires is shown in bold and Barnes in standard weight lines. The slight discrepancy between the arcs of normal working area by the different authors emphasises the fact that even under scientific analysis, there is a degree of subjectivity. These arcs also represent the findings based on an average male and in reality, all human beings have slightly different proportions. Despite this, there is clearly much overlap in the findings and so this diagram was chosen to serve as a useful approximation.

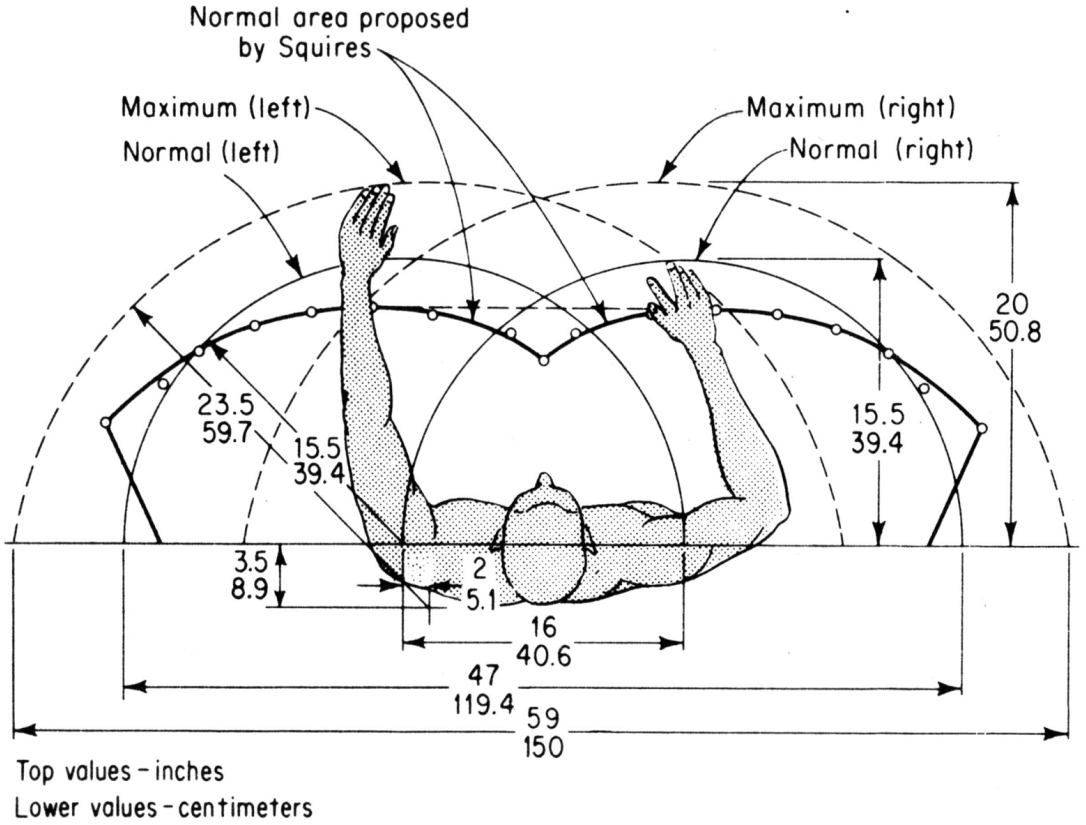


Figure 5.18: Ergonomic diagram showing normal working areas as suggested by two different authors. The arc based on findings from research by Barnes [1968] is shown as a standard weight line and by Squires [1956] as a bold weight line. Maximum working area is also included.

5.4.2 Method of analysis

It should be noted that in using the diagram in Figure 5.18 to explore the issue of hand placement when holding the horn, a number of assumptions or approximations have to be made for the purpose of systematic analysis. Given that the diagram refers to a horizontal working plane, it has been assumed that the horn is held with both hands approximately level. In practice different players may have positioned their hands at slightly different heights. Also, the head in the diagram is pointing forward, therefore an assumption has been made that the mouthpipe is also positioned directly in front of the head and perpendicular to the line of the shoulders as shown in Figure 5.19. For ease of discussion, all horns will be referred

to and analysed as if they were right handed, i.e. the left hand near the mouthpipe and the right hand near the bell, but left-handed instruments were not uncommon prior to the invention of the valve at the beginning of the nineteenth century.

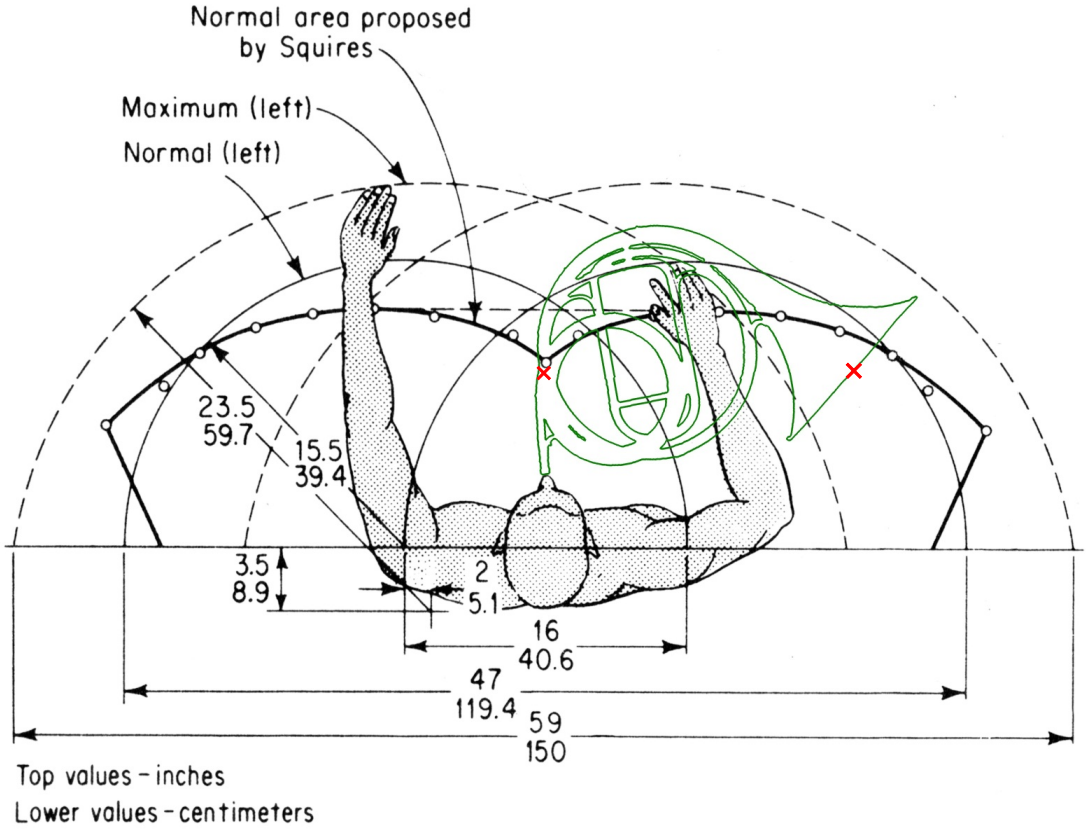


Figure 5.19: Ergonomic diagram showing an outline of a nineteenth-century hand horn by the maker Besson (GB.E.chick, 2006.1) superimposed. Red crosses mark the approximate location of the hands and are shown here to be close to the normal working area arcs.

Initial estimations of a comfortable playing position were made by digitally manipulating images of the photographed horns in order to reveal only the outline, which was then scaled and superimposed on the diagram (see Figure 5.19). The horn displayed in this example is an outline of a mid nineteenth-century hand horn by the maker Besson (GB.E.chick, 2006.1) This was an important horn to include in the initial analysis process because it is an instrument which was designed to be played with a comfortable and flexible use of the hand in the bell area. It was therefore helpful in verifying whether or not this diagram might prove to be a

valuable aid in assessing horn playing ergonomics.

The approximate right and left hand positions for this instrument are represented by red crosses. The location of the red cross to identify the approximate position of the hand in the bell was chosen for the same reasons as those discussed previously in Section 5.3. In practice, the exact position of the each hand would have varied slightly from player to player.

It is evident from the diagram in Figure 5.19, that the approximate hand positions for this nineteenth-century hand horn are both very close to the normal working area arcs, which would suggest some validity concerning the use of this diagram for the following exploration of horn ergonomics. In addition, it was found that the modern horn (GB.E.chick, 2001.1), designed to be supported with the hand in the bell, although with a more stationary hand position, also complied with the diagram, see Figure 5.20.

Presenting all of the horn outlines on one diagram would become over-complicated, therefore in order to simplify the analysis and to allow comparisons to be made more easily, only the point representing the approximate right hand position has been plotted for each horn, see the graph in Figure 5.21. This is the same reference point that was used to calculate the dimensions shown in the previous graph in Figure 5.17. The left hand position has not been plotted, partly because it is less relevant to the discussion on hand-in-the-bell technique, but also because on the majority of horns, it was found to lie close to the arcs in the diagram. The only exceptions were the large hooped hunting horns which would most likely have been gripped in a different position altogether.

The graph in Figure 5.21 shows the data from all the horns included in this survey. Even in this simplified format, where only the right hand position is displayed, there is still too much information to draw any clear conclusions and so the analysis in the following sections is based on graphs showing subsets of the data.

The horns are grouped into three general types: crooked horns, fixed pitch horns and hunting horns. These three types of horn represent different stages in the development of the instrument. It should be noted that hunting horns are also

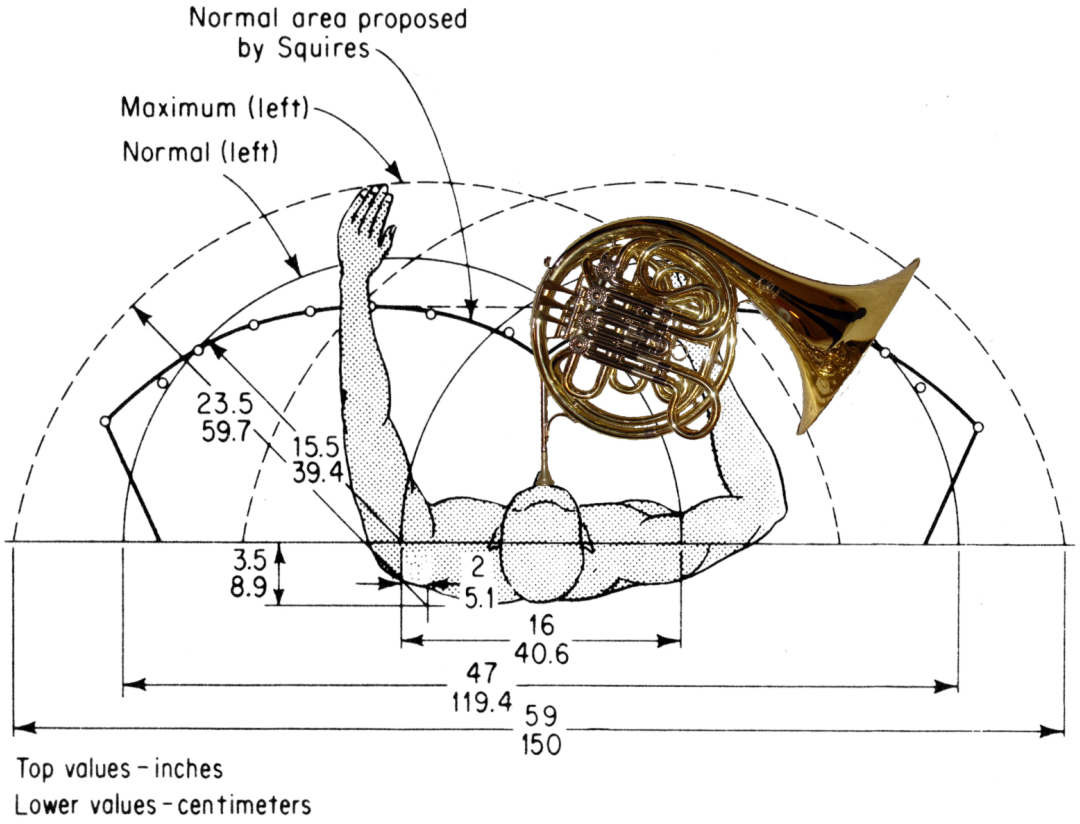


Figure 5.20: Ergonomic diagram showing a photograph of a modern horn by the maker Paxman (GB.E.chick, 2001.1) superimposed. The left hand grip and horn bell are shown here to be close to the normal working area arcs.

examples of fixed pitch instruments but for the sake of the following analysis, the hunting horn group refers to only wide coiled instruments with a corpus diameter greater than 400 mm. Within the fixed pitch horn group, some of these instruments may have been used in the hunt, some in the concert hall, and others may have been used in both situations as many of these instruments were made during the period of transition when the horn was becoming an increasingly important member of the orchestra.

The same format is used for all graphs; the data points are categorised by colour corresponding to the date of manufacture, where bright red indicates the most modern instruments and dark green, the most historic, see the scale on the right. The different marker shapes represent the different geographical regions; the star

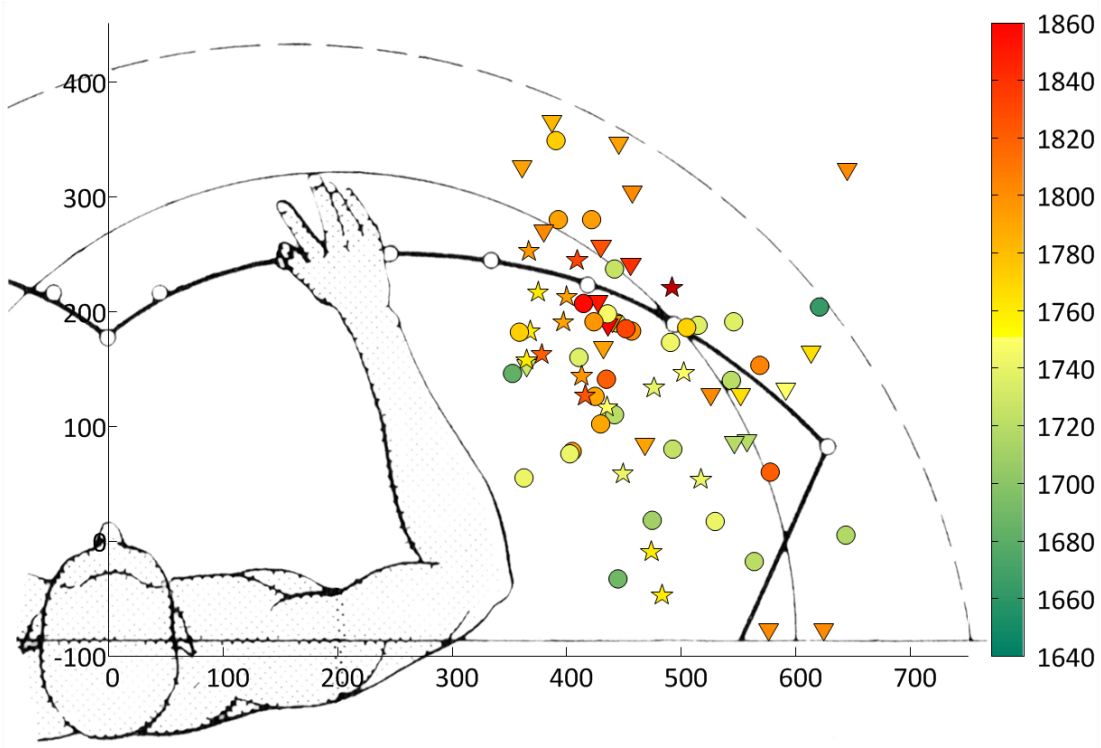


Figure 5.21: Ergonomic diagram showing the approximate right hand position for all horns included in the dataset. The symbols represent different geographical regions: England (star), Germany (circle), and the remaining horns (triangle). The approximate date of manufacture is represented by the graded colour chart on the right of the figure.

shape refers to instruments of English origin, the circle to horns from Germany, and the triangle represents all of the other instruments, mainly consisting of those from France.

5.4.3 Crooked horns

Of the three horn groups analysed, the crooked horn group represents the most recent stage in the development of the eighteenth-century instrument (the other two groups being fixed pitch and hunting horns). Most of these crooked horns would have been intended to be played with the hand in the bell and so it is interesting to see how they correspond to the ergonomic diagram. Figure 5.22 shows the results.

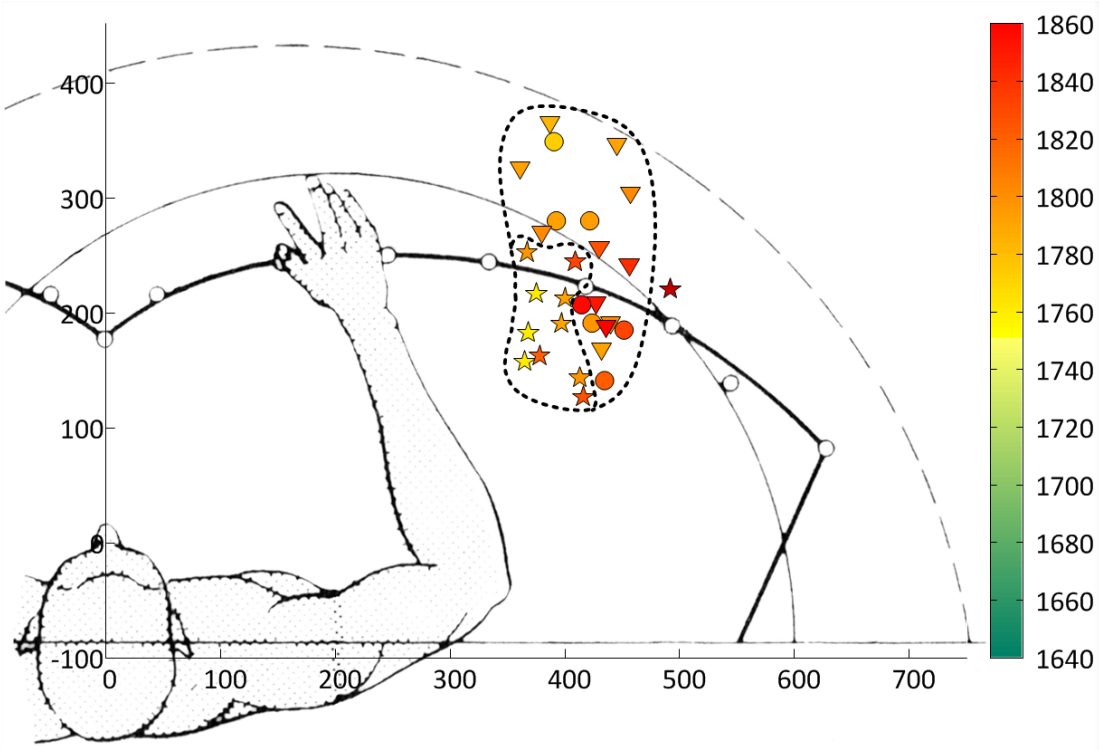


Figure 5.22: Ergonomic diagram showing the approximate right hand position for all crooked horns included in the dataset. The symbols represent different geographical regions: England (star), Germany (circle), and the remaining horns (triangle). The approximate date of manufacture is represented by the graded colour chart on the right of the figure. Dashed annotation shows the divide between English instruments and those from other regions.

It is encouraging to see that most of the points are located either close to the normal working area of the arm, or at least within the maximum working area (long dashed arc). There is a cluster of points close to the bold arc, many of which are bright red in colour. This shade refers to the most recent instruments in the dataset, the mid-nineteenth century horns. As hand technique became more widely adopted and composers became aware of the new potential of the instrument, the player was required to perform ever more dexterous feats with their right hand in the bell, and so by the mid-nineteenth century, 'hand' horns would have been designed for optimum ergonomic comfort relating to hand access in the bell. This assumption is corroborated by these results in the ergonomic diagram (Figure 5.22).

The graph in Figure 5.22 has been annotated with a dashed enclosure to show a separation between horns made in England (stars) and those made in the rest of Europe. The dark red star which sits outside of the enclosed dashed line represents the modern horn by instrument maker Paxman (GB.E.chick, 2001.1), and this point will appear on all of the following graphs for reference. This geographical divide seems to suggest that in general, English horns were designed such that the player's right hand would be slightly closer to the body, assuming the use of hand technique. There is however another significant difference in the design of English crooked horns compared to those from other regions; this concerns the type of crooking system in use. A common feature of English instruments is the crook and coupler system, whereas elsewhere in Europe a terminal crooking system was much more popular. See Section 4.1.3 for further discussion on these systems and Figure 4.6 for photographs.

From an ergonomic point of view, the crook and coupler system results in a significant amount of variation of both right and left hand positions, depending on the number of couplers in use for a particular key. The more couplers in use, the further away from the player's body the horn is located. In the terminal crooking system the variation is much less because generally only one crook is needed. Even the difference between short and long terminal crooks is minimised by coiling the longer lengths of tubing in a more compact manner. This may help to explain why English instruments were designed with the instrument generally closer to the body of the player, to allow room for expansion making it possible to reach the bell, even when numerous couplers were in use.

5.4.4 Fixed pitch horns

The results for the fixed pitch horn group are shown in Figure 5.23. Compared to the results from the crooked horn group in Figure 5.22, these fixed pitch instruments are generally from an earlier period, as demonstrated by the greater number of green and yellow coloured points on the graph, rather than red and orange. The dashed line annotation from the previous graph has been included on this graph for comparison.

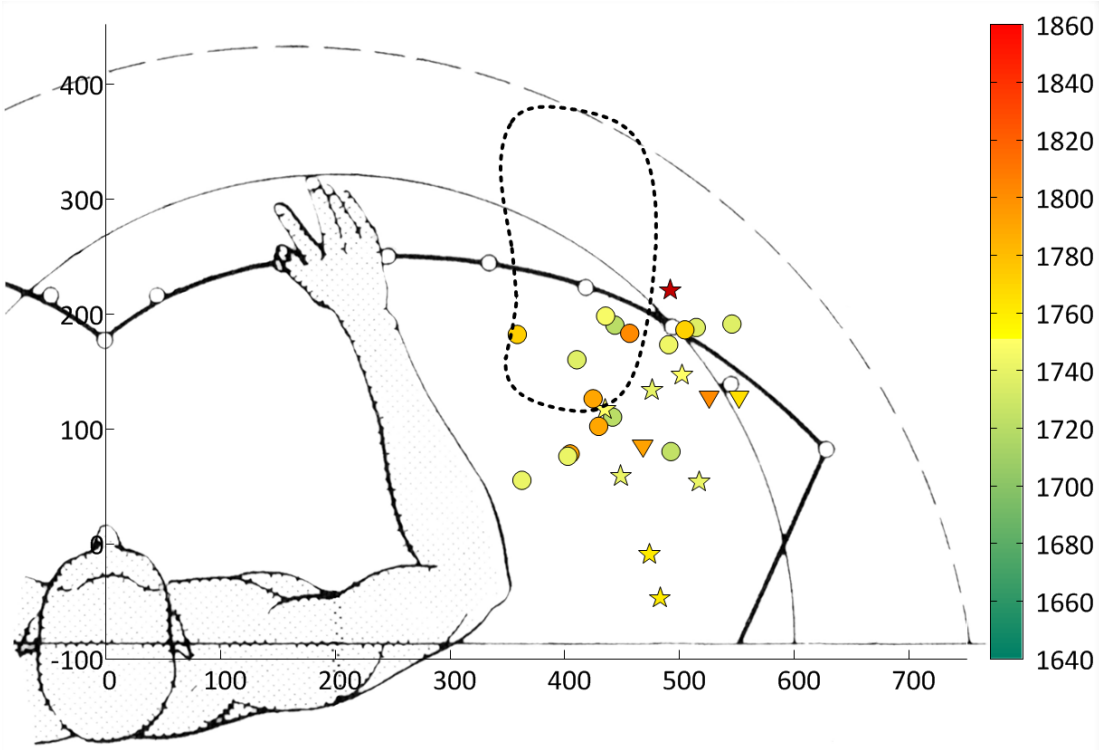


Figure 5.23: Ergonomic diagram showing the approximate right hand position for a sample of fixed pitch horns. The symbols represent different geographical regions: England (star), Germany (circle), and the remaining horns (triangle). The approximate date of manufacture is represented by the graded colour chart on the right of the figure. Dashed annotation shows the location of points from the crooked horn group in Figure 5.22.

In general, the fixed pitch horns appear to have their bells located closer to the body of the player than the crooked horn group, with the majority of the data points occurring within, not just the maximum working area, but also within the normal working area arcs. The cluster of points is also further to the right of the dashed line annotation, indicating a wider distance between right and left hand positions if hand technique were to be employed on these fixed pitch instruments.

There are several points however, which overlap into the crooked horn group area. The orange-coloured symbols in this region are perhaps not surprising because they represent instruments dated from approximately the late eighteenth century, but two early eighteenth-century German horns stand out, shaded as pale green

circles: these represent a horn by Ehe dated about 1720 (D.N.gnm, MIR 74) and one by Werner, dated 1735 (CH.B.hm, 1980.2099.). It is perhaps significant that a horn by Werner should appear to have a comfortable hand position, because it is known that he worked closely with Hampel in the 1750s on the design of horns. As mentioned previously Hampel was a strong advocate of hand horn technique (see Section 2.2.1 for further discussion on his role in this).

Whether these two early German horns were designed specifically to support the use of hand in the bell, or whether this was purely coincidental, the bell would clearly have been in a very convenient place for players to experiment with hand technique as early as the second decade of the eighteenth century.

5.4.5 Hunting horns

The graph in Figure 5.24 shows the final set of data points representing the wide-hooped hunting horns. Due to the large diameter of their corpuses, the bells for these horns are located at the furthest distance from the body of the player compared to the previous two groups, appearing on the graph, mostly to the far right. Within this group, there are examples of both early hunting horns (shaded green/yellow) and more recent instruments (shaded orange/red). Several of the points are located outside of the normal comfortable working area with one point occurring beyond the dashed line of maximum reach. To play this instrument with the hand in the bell would clearly be extremely difficult, if not impossible.

According to the maximum reach arc on this diagram (Figure 5.24), many of these wide-coiled hunting horns are designed such that the bell is within reach of the hand. This may perhaps seem slightly surprising to any horn player who has held one of these large unwieldy instruments. There are limitations however, to the interpretation of this type of diagram; although it provides a more useful insight into horn ergonomics than the abstract measurements from Section 5.3 (e.g. the graph in Figure 5.17), there is still much that cannot be deduced from these diagrams. Information such as corpus size, which in turn affects the weighting of the instrument when supported at the bell. Another important aspect of the bell when

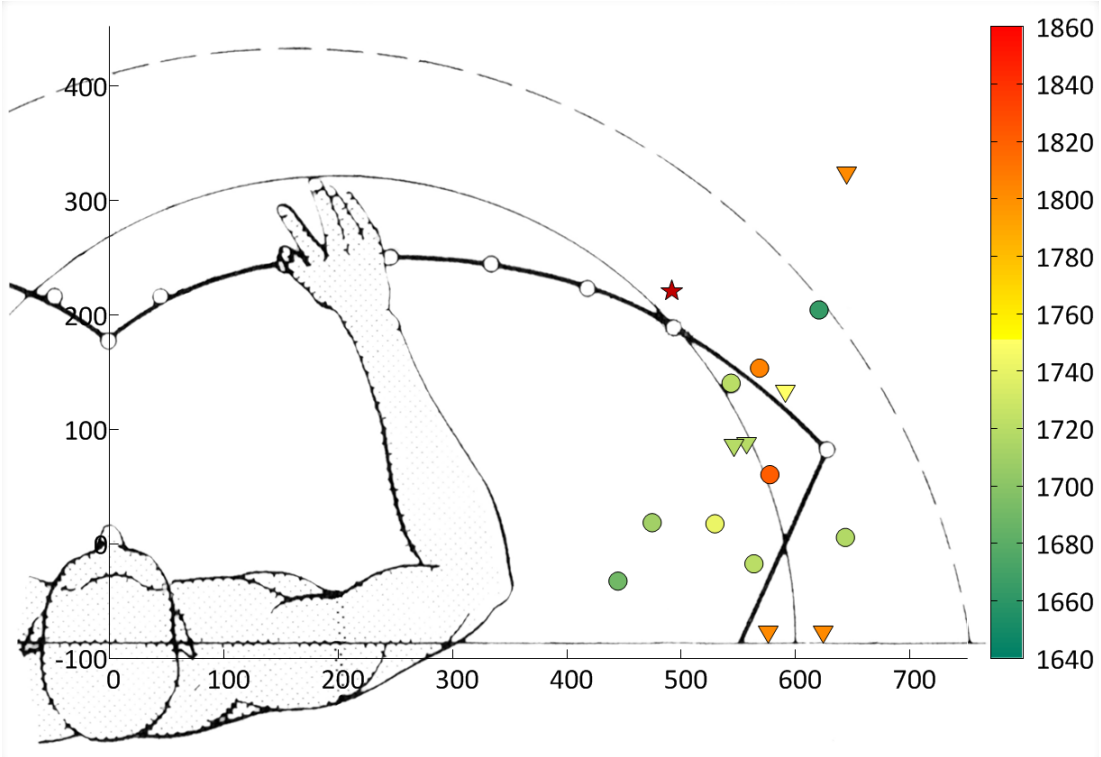


Figure 5.24: Ergonomic diagram showing the approximate right hand position for all hunting horns included in the dataset. The symbols represent different geographical regions: England (star), Germany (circle), and the remaining horns (triangle). The approximate date of manufacture is represented by the graded colour chart on the right of the figure.

considering hand technique is the angle of the bell. On many large hunting horns, the bell does not point in a convenient direction for easy insertion of the hand, making it very difficult to hold the instrument with the hand in the bell.

5.5 Conclusions

Design and ergonomics in horn playing is a subject area which has previously received very little attention in academic writing. The research included in this chapter was intended as an initial investigation into whether new light can be shed on eighteenth-century horn manufacture and playing technique when analysed from a design and ergonomic perspective.

The first phase of analysis involved comparing outlines of early horns and it was found to be particularly useful for exploring consistency in the manufacturing practices within workshops. This method was also conducive to the processing of data on a large scale for the purpose of analysis, but a disadvantage was that a limited number of outlines could be compared at any one time. The analysis was also relatively subjective and so a more systematic and objective approach was considered for the next stage of the investigation.

Certain horn dimensions were measured, chosen due to their ergonomic significance, and each set of values was plotted against date of manufacture. From these results it was clear that in the eighteenth century, there was great diversity in horn design, apparent due to the wide scatter of data points. Several trends were observed as horn design changed over the course of the eighteenth century including a slight increase in bell size and a greater standardisation in corpus diameter. On the other hand, the most seemingly promising dimension in terms of ergonomics, the distance from the mouthpiece to the bell, showed no obvious correlation over time. This unexpected result led to the idea for a new approach, an amalgamation of the first two types of analyses.

An ergonomic diagram formed the basis for the final stage of the investigation, allowing the horn to be viewed as a whole, but in a systematic manner, in the context of comfortable arm reach predictions. The results highlighted three clear stages in the design of the horn; crooked horns, fixed pitch horns, and hunting horns. Within these three groups, interesting trends were observed in connection with regional variation, such as the comparisons between English horns and those from elsewhere, possibly as a result of different crooking systems.

There is great potential for further work to be carried out in this area. For example, it would be interesting to explore the ergonomic implications of bell angle relative to the body of the player, an aspect of design which none of the previously mentioned approaches was able to take account of. In the related field of biomechanics, there are several predictive equations which have been created in order to estimate the maximal force when lifting, dependant on the posture of the arms. This research has been carried out in order to help design workstations and increase employer awareness to the health threats of performing certain tasks

[Kedzior & Roman-Liu, 2006; Roman-Liu & Tokarski, 2005], but it could also be applied to the task of horn playing. Not only could this approach provide a more precise indication of a comfortable playing position, but the horn dimensions could be used as the input to a predictive equation in order to rank the instruments based on this parameter. It would be interesting to observe if there is a correlation between the predicted maximum force value due to a playing position imposed by the horn, and the development of horn design in relation to hand technique.

Chapter 6

Bore profiles

The comparison of bore profile dimensions from a large database of horn measurements forms the basis for this final results chapter. The importance of the bore profile in the context of analysis techniques carried out in the previous chapters is discussed in the introduction (6.1). The next section describes the process for taking detailed bore measurements and how the data was able to be analysed on a large scale (6.2). In the main body of the chapter, a number of examples are presented of how bore profile analysis can bring to light interesting aspects of brass instrument manufacture (6.3), and the final section looks at the new possibilities opened up by this method of research (6.4).

6.1 Introduction

The bore profile of a brass instrument can be described as the variation in the cross sectional area of tubing along its length, and this shape is of fundamental importance to the identification of the instrument, both in terms of physical characteristics, and in terms of its influence on sound and acoustics. It is easy to see how the physical aspect of the bore profile can aid identification, but the link between the sound an instrument makes and its bore profile shape is slightly more removed.

The acoustic properties of a brass instrument, and hence the sound it produces, are primarily dependant on the shape of the air column of the instrument, or as a close approximation, the shape of its bore profile. Bends in the tubing of a brass instrument have been found to have a small effect on the acoustics of the instrument [Braden, 2006; Félix *et al.*, 2012; Myers & Parks, 1995], however it is the varying diameter of the tubing along its length which is the dominant factor. It is also noted that the radius of bends on early orchestral horns is generally larger than on other brass instruments, and for this reason the acoustic effect of bent tubing has not been considered in the following analysis.

As a listener, various aspects of the sound of a brass instrument provide clues as to the type of instrument being played, such as note transients (both starting and transition) [Logie, 2012; Stevenson, 2009], or the rate at which the tone becomes brassy during a crescendo [Myers *et al.*, 2012]. For example, the shape of the tubing on a horn is generally more conical than that on a trombone, which means that the listener is able to distinguish between the tone quality of these two instrument groups.

This acoustic distinction between types of brass instrument can be applied at a much more subtle level too, as demonstrated by the discussion on the sound of eighteenth-century horns in Chapter 3. Identification based on acoustic properties was also mentioned in Chapter 4, where the input impedance curve was analysed in its capacity as a unique identification of the response of an instrument. Thus the acoustic properties of a brass instrument and its identification are both intrinsically linked to the shape of its bore profile. The physical aspect of the shape of the horn was discussed to some extent in Chapter 5, but the emphasis was on the wrap of the horn rather than on the shape of the bore profile. This dual nature of the design of a brass instrument makes identification and classification both interesting but also slightly confusing.

Characteristics of both the wrap and of the bore profile have been used to identify brass instruments historically, and this has created some ambiguity; two instruments may have a similar layout of tubing, so are classified as the same type, but have very different bore profiles resulting in different acoustic characteristics. For example, a Wagner tuba by the instrument maker Mahillon sounds much more

trombone-like than a Wagner tuba by the maker Alexander due to the very different nature of their bore profiles, although they share a similar upright, oval wrap [Norman, 2009]. See Figure 6.1 for a bore profile comparison. The opposite is

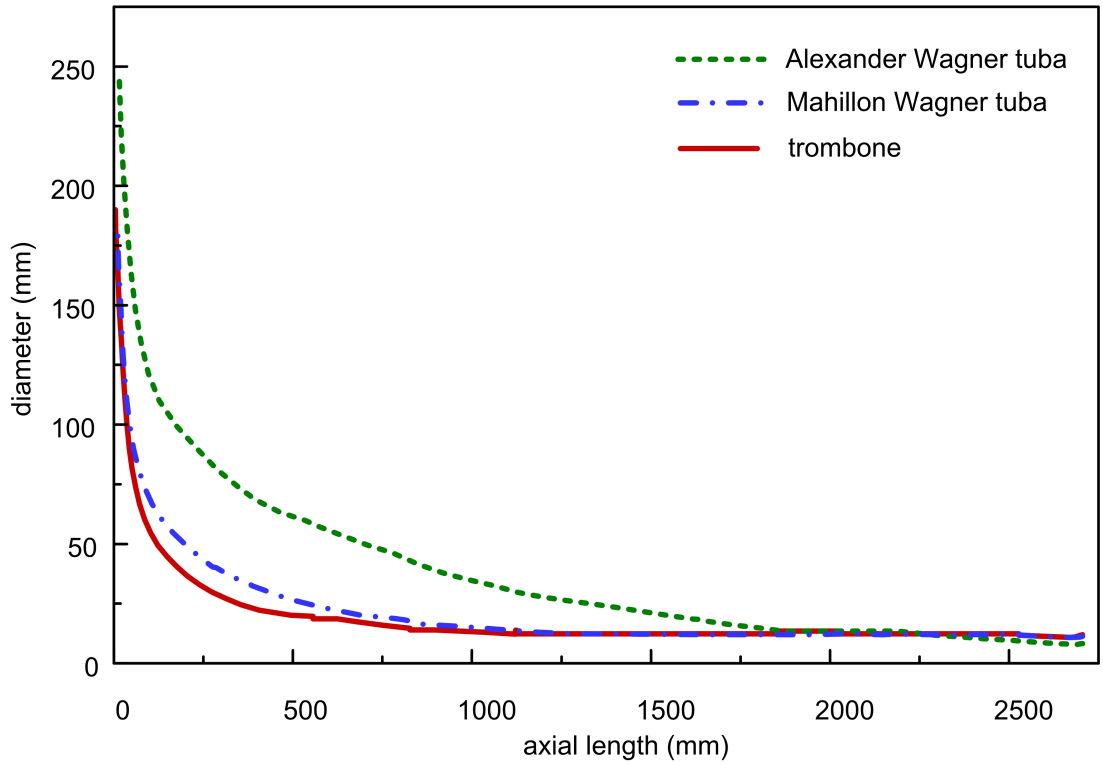


Figure 6.1: Bore profile comparison of two Wagner tubas by makers Alexander and Mahillon. A typical trombone bore profile is also displayed to show the similarity in shape with the instrument by Mahillon.

also true; the bass trumpet for example, has a bore profile which is very similar to that of the trombone, but due to the layout of the tubing it has been classified as a member of the trumpet family, despite sounding more like a trombone (see Figure 6.2 for a visual comparison [Myers *et al.*, 2005]).

The identity of a brass instrument is a broad issue concerned mainly with classification and taxonomy within the brass instrument family, but these examples help to illustrate the two main aspects of the design of a brass instrument: the bore profile dimensions and the layout of the tubing. Within one type of brass instrument, analysis of wrap and bore details can provide useful information about its origins. Instruments made in a particular workshop often share similar design features; this

Figure 6.2: Photographic comparison of a bass trumpet (top) and a trombone (bottom), showing two very different wraps, however they share a very similar bore profile shape [Myers *et al.*, 2005].

might include aspects such as the layout of the tubing, but also smaller details like stays, seams, gussets, garlands, ferrules etc.

When carrying out historic instrument research, it is common to begin by examining aesthetic features such as these, particularly when trying to identify anonymous instruments. Differences in design features are relatively easy to detect and compare on initial visual inspection. For example, two horns from the workshop of Nuremberg by instrument maker Haas are shown in Figure 6.3, and it is clear to see that each horn has its own distinctive character. By looking only at these photographs it is apparent that they have a very different corpus size,* and on closer inspection, the photographs of the design details vary significantly too. It is much more difficult however, to comment on how the shape of the tubing compares after carrying out only a visual inspection.

*The instruments have been scaled relative to each other, as is the case with all figures in this thesis which include more than one image of an instrument.

Figure 6.3: Photographs showing initial visual observations of the design features on two horns. Left: Haas (D.N.gm, MI 179) dated 1724. Right: Haas (CH.B.hm, 1880.72.) dated 1682.

Bore profile analysis is generally a less well documented area of brass instrument research, although equally revealing. This is largely because accurate comparisons can only be made after taking detailed, and often time consuming, measurements of the tubing. As a means of aiding identification however, comparison of bore

profiles can be extremely helpful. In the process of making a horn, large sections of the bore profile are shaped by moulds called mandrels. It is likely that given the expense and lengthy nature of creating a mandrel, the number produced would have been limited, and these would have been used over a long period of time. This information helps to narrow down the potential origin of a horn if a match with another instrument is found.

The process of trying to match the bore profile of different instruments raises another problem. Although the detailed measurements of the tubing allow graphs to be created providing a clear indication of the shape of the instrument (for example, Figure 6.1), the differences between instruments from the same family are often very subtle and easy to miss when inspecting these graphs visually. It is also extremely time consuming to manually manipulate the data in order to compare one instrument to every other instrument in a large database of over one hundred measurements.

For these reasons, it was decided that a software tool should be created which would enable easy comparison of one bore profile measurement with others in the database, provide an indication of the closest matches to the initial target bore profile, and also details of the variation between matches. The rest of this chapter describes the function of this software in more detail and discusses the benefit of such a tool for bringing to light interesting aspects of eighteenth-century horn design and manufacture. The results are discussed in the context of analysis techniques used in the previous three chapters of this thesis.

6.2 Measurements and analysis

The bore profile can be determined reasonably accurately by using simple measuring equipment and techniques to record the diameter at different points along the length of tubing on an instrument. This was carried out in two separate stages.

The bell was measured using a set of Perspex rods with varying lengths which

are based on a logarithmic scale. With the aid of a special fitting, the rods were attached perpendicular to a prepared rule and inserted into the bell of the instrument until the rod length corresponded to the internal bell diameter. Depth of insertion could then be read easily from the rule and was noted against bore diameter (rod length). For this part of the measurement process, the diameter was a fixed set of values (the rods) and the depth of insertion varied for each new instrument. Damage, denting or repair work was avoided where possible.

Each recorded dimension consisted of an average of two measurements. Variation in the degree of accuracy of the measurements was accounted for by noting down half the difference between the two measurements, plus 1 mm as a basic tolerance. Any discrepancies in the measurements could then be discovered more easily; for example, an inconsistency in the data over a few measurements might indicate a small dent whereas inconsistencies over a larger number of measurements might indicate a slightly elliptical bell shape.

The main body of the instrument was measured from the opposite end, from the mouthpiece receiver. Callipers were used to measure the internal bore diameter where access would allow, i.e. the start of the mouthpipe, crook receiver, and the entry and exit of all removable sections of tubing. Marked string and plastic callipers were then employed to measure the axial distance at approximately 100 mm intervals (or less). The thickness of the metal was accounted for by subtracting double the estimated value of wall thickness, so that an internal bore measurement could be calculated. Care was taken to ensure that the line of measurement was as close to the axial line as possible. An example of a rough draft measurement sheet is shown in Figure 7.1.

Both sets of measurements, bell and corpus, were then combined to create a record of the complete bore profile of the instrument. This manual method of measuring the bore profile is relatively time consuming but it is still more accurate than a number of faster processes such as pulse reflectometry [Kemp *et al.*, 2008], where an acoustic signal is sent down the length of the instrument and the reflections are recorded. The information received from the reflections can be manipulated in order to provide a measurement of the bore profile and although this method is not yet as accurate as taking physical measurements, more sophisticated techniques

such as this are improving all the time.

The raw measurement data was then turned into a graph in order to provide a visual representation of the bore profile of the instrument. An example can be seen in Figure 6.4. This is the bore profile of a horn by the London maker Nicholas

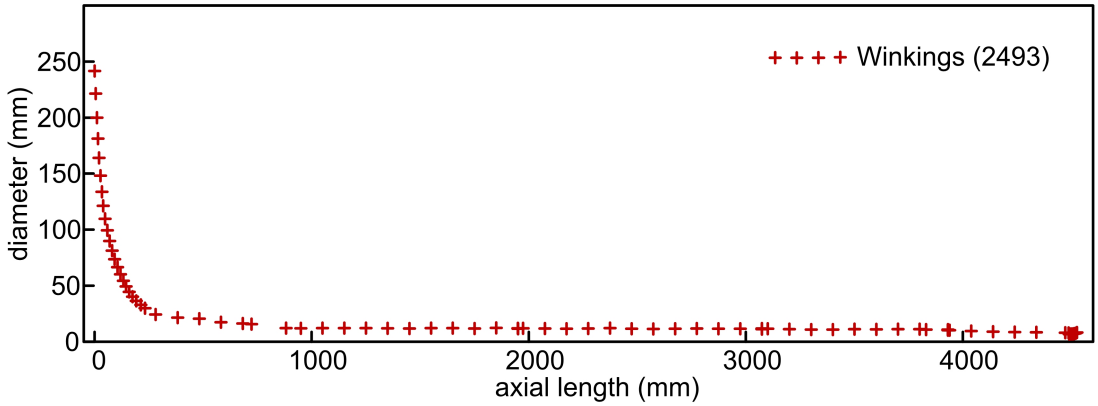


Figure 6.4: Raw bore profile data plotted from a horn by Nicholas Winkings (GB.E.u, 2493). Bell flare is shown to the left, mouthpipe to the right and each red cross corresponds to a separate physical measurement.

Winkings, pitched in D, made around the middle of the eighteenth century (GB.E.u, 2493). The length of the instrument is plotted against internal tube diameter and each cross corresponds to a separate measurement. There are many more measurements at the bell and at the start of the mouthpipe (far right and left of the graph), and fewer along the near cylindrical section in the middle. This is partly because access to measure the internal diameter of the instrument is easier at either end, but also because for the purpose of the following research, these tapered sections are of greater interest than the straighter lengths of tubing.

The bell is shown to the left and the mouthpipe to the right but the the scales of the x and y axes are different. It is displayed in this distorted form so that differences in the wider diameter tubing can be seen more easily. If the bore of a horn was to be plotted to scale, it would be extremely elongated and have the approximate dimensions shown in Figure 6.5, essentially, the horn 'unwound'.

Detailed measurements of over one hundred instruments have been included in the bore profile comparison database. Further information about these instruments

can be found in Appendices A and B.

Figure 6.5: The approximate bore profile of a horn if it were to be drawn to scale and straightened out.

6.2.1 Comparison software

The bore profile comparison software was created in order to fulfil two main objectives. It had to be able to process a large database of measurements relatively quickly and to be able to compare the bore profiles systematically in order to find similar shapes [Norman & Chick, 2012].

Each bore profile measurement was recorded as two columns of data: internal bore diameter and axial length. This was used as the input file format for the software programme. During the first stage of processing, the computer programme creates a bore profile based on an interpolation of the measured data, see Figure 6.6. In

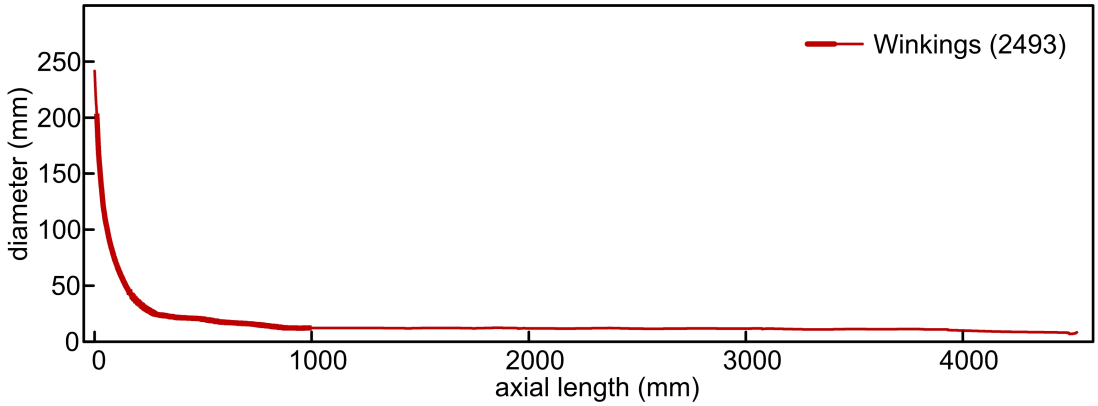


Figure 6.6: Interpolated bore profile data plotted from the measurements in Figure 6.4. The thick red line corresponds to a specific selection of the bore chosen for comparison and the the thin red line shows the rest of the full bore profile.

the examples included in this chapter, linear interpolation was used as the curve fitting method and was found to be adequate given the large number of data points measured. The software also allows for other curve fitting options such

as a smoothed spline or the creation of a curve based on a series of Bessel horn sections. Smoothing options could be useful when fewer measurements have been recorded or if a small section of the instrument has obviously been altered due to damage or adaptation.

Another useful option provided by the software is the ability to choose a precise part of the bore profile for comparison. Where instruments have been badly dented, it might not be desirable to include the damaged section of the bore profile in the analysis. For example, the rim of the bell on a horn is extremely fragile and many historic instruments have undergone repairs in this area due to wear and tear over the years. Another exposed part of the horn is the mouthpipe which is sometimes found to have been replaced; this might have been as a result of damage, or it could be that this section was intentionally modified at a later date in order to adjust the tuning, or was adapted to accept crooks. In these more ambiguous cases, the option to specify an exact length and section of bore profile for comparison might be convenient.

Many of the bore profile comparison examples included in this chapter focus on the profile of the bell of the horn, the section of the instrument shaped by the bell mandrel. The graph in Figure 6.6 shows an example of a bore profile where only part of the bell has been selected as the target for comparison. The selection can be seen as the bold line which stops at 1000 mm. The thin line indicates parts of the instruments which have not been included in the analysis; in this example, a small section at the very edge of the bell rim and the main body of the corpus.

The selected part of the target (or chosen) bore profile is then compared to the other bore profiles in the database and the programme assesses the extent to which the target section of tubing matches the shape of every other instrument profile. The results are ranked based on the minimum least squares difference between each comparison. Effectively, what the software tool does when carrying out the analysis, is to 'slide' the selected target bore profile along the length of the instrument being compared until it finds the best match with an equivalent length of bore. This same process is carried out on all of the instruments in the database.

An example of a typical output from the comparison software is shown in Figure 6.7. The part of bore profile compared in this example is the highlighted

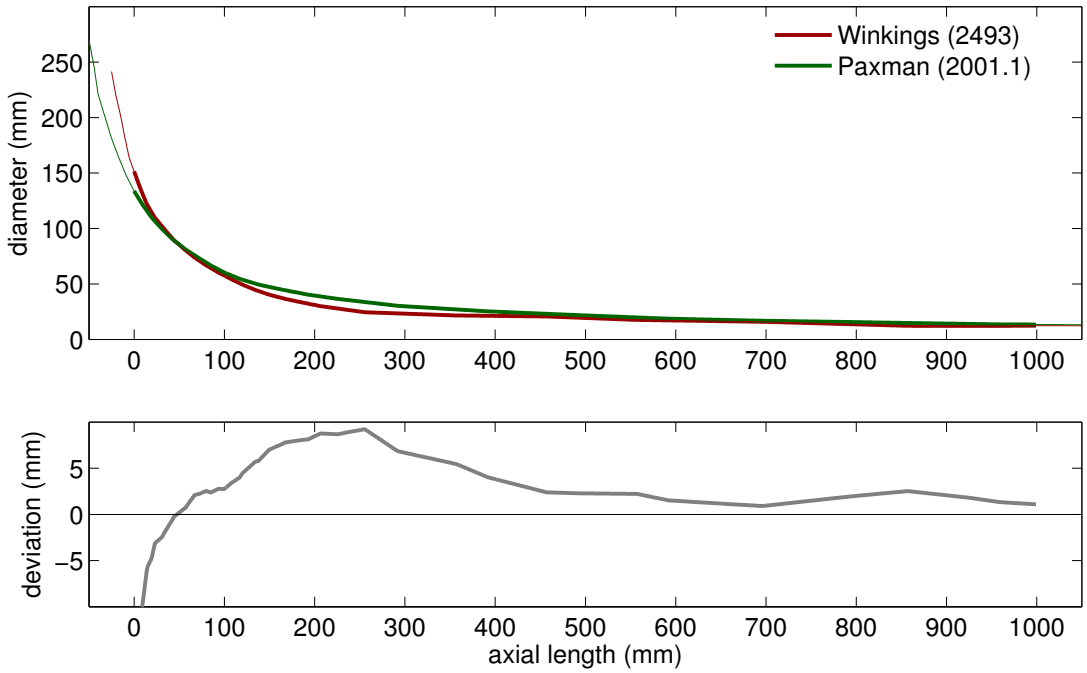


Figure 6.7: Example of an output from the bore profile matching software showing a comparison between a modern horn by Paxman (GB.E.chick, 2001.1) and the early horn by Winkings (GB.E.u, 2493) from Figure 6.6.

selection from Figure 6.6; note that the x-axis only goes as high as 1000 mm, showing only the bell section. Here we can see a comparison between two very different horns: the mid eighteenth-century instrument by the maker Winkings of London is compared to a modern, twenty-first century instrument by the manufacturer Paxman Horns of London (GB.E.chick, 2001.1). The two bore profiles are shown in the top graph, and the extent to which they differ is displayed in the lower graph.

In this example, the computer programme has attempted to find the section of tubing on the Paxman horn which most closely matches the target section of tubing on the Winkings horn, but the graphs clearly show that these two instruments are not a particularly good match. This is not surprising since a time period of over two hundred years separates these horns. The superimposed bore profile comparison

graph (top graph in Figure 6.7) shows that the bell flare on the Winkings horn (red curve) undergoes a more rapid expansion than that on the Paxman instrument (green curve); whereas the maximum diameter of the selected tubing on the Paxman horn is slightly less than on the Winkings horn at the start of the graph, the tubing on the Paxman then becomes significantly wider than the Winkings horn, slightly further into the bell (at around 200-300 mm, axial length).

This can be seen most clearly in the lower graph in Figure 6.7 showing the deviation between the two bore profiles. The curve on this graph indicates a fluctuation at least as wide as plus or minus 10 mm. The deviation results have been slightly cropped at the start because it was decided that comparisons between instruments would be easier, and differences more noticeable, if the same y-axis range was included in all similar output graphs shown in the rest of this chapter.

6.2.2 Computational modelling

The detailed measurement of the bore profile of a brass instrument can be used as the input to a computational model in order to predict aspects of its acoustical behaviour. Models such as this have been developed at the University of Edinburgh by Alastair Braden [2006] and Stefan Bilbao [2011] and have been used to predict acoustic impedance curves based on the details of the shape of the bore profile. One of the major advantages of this type of analysis, is the possibility of assessing the playing characteristics of damaged historic brass instruments which are no longer in playing condition. In these cases, extrapolated measurements of the bore profile may be used as the input to the model. An example of this type of analysis is discussed in Section 6.3.4 and a comparison between measured and modelled impedance is shown in Figure 6.32. Computational models may also provide an alternative method of analysis in cases where it is not possible to take acoustic measurements of certain instruments, either due to lack of availability of equipment, or sensitivity of museum management to experimental testing procedures.

6.3 Bore profiles

Questions surrounding the history of horn development are best answered when the instrument is considered in the context of many other similar instruments, a potentially difficult prospect when examples of surviving early horns are spread far and wide in collections across the world. The only option for the researcher is to try and glean as much information from the horns as possible by examining instruments and recording the details for further analysis at a later date. Photographs are useful for providing a visual representation of an instrument, but when combined with the measurement of the bore profile, the potential for historical insight becomes much greater.

Previous historic instrument research has tended to focus mainly on the comparison of visual aspects of manufacturing and design details, but through additional information provided by the comparison of bore profiles, there is now the possibility of finding new connections between instruments and workshops, which can lead to new avenues of research.

In the rest of this chapter, several examples are provided of the interesting and sometimes unexpected links which have been revealed about the shapes of different early horns through using the bore profile comparison software tool. These connections and observations have sparked further investigation, drawing on some of the interdisciplinary analysis techniques discussed in previous chapters of this thesis.

6.3.1 Workshop variation

The previous example in Figure 6.7, of an output from the comparison software, showed two horns with very different bore profiles from two different eras, but at the other end of the scale, the bore profile matching tool has allowed the issue of consistency and uniformity in manufacturing to be explored. This topic was examined in Section 5.2.2 by comparing the outlines of horns, but a more systematic and detailed analysis is possible using a computer programme.

It seemed an obvious first step to look at instruments from the same maker or workshop and see the extent to which their bore profiles either agreed or differed. By looking at this aspect of consistency in the manufacturing process, it provided a useful point of reference for considering the comparison of horn bore profiles from *different* instrument makers.

An example of a bore profile comparison which resulted in a close match can be seen in Figure 6.8. These graphs show a comparison of two horns by the instrument

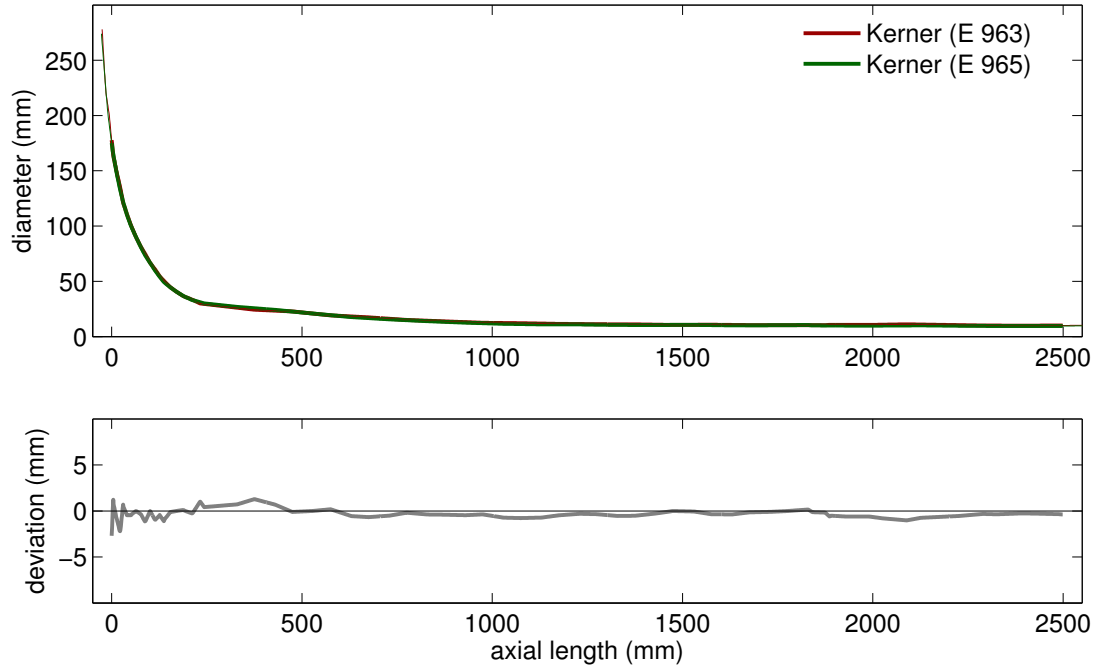


Figure 6.8: Bore profile comparison of two horns by the maker Anton Kerner, dated 1777 (CZ.Pnm, E 963) and 1769 (CZ.Pnm, E 965). The graph shows that they are an extremely close match.

maker Anton Kerner who was active in Vienna during the second half of the eighteenth century (CZ.Pnm, E 963 and E 965). The match is so close that the separate bore profiles are almost indistinguishable from each other in the top graph, and any small inconsistencies that do occur have been amplified and are displayed on the bottom graph; the sections of bore profile compared, which covers the majority of the length of both instruments, are shown to deviate by less than a few millimetres from each other. The slight fluctuations that do occur are most likely due to small dents which the instruments have accumulated over the intervening years. From

these results it can be shown that Kerner was extremely consistent in his approach to making horns.

Photographs of the two Kerner horns can be seen in Figure 6.9 along with a close-up of the signature on both bell garlands. From the dates inscribed on the garlands,

Figure 6.9: Photographs showing two horns by Kerner and details of the inscriptions on the bell garlands. Left: Kerner (CZ.Pnm, E 965), dated 1769. Right: Kerner (CZ.Pnm, E 963), dated 1777.

it would appear that these two instruments were made about eight years apart, in 1769 and 1777 respectively. There are also some small differences concerning the manufacturing details, such as the double stays on both the mouthpipe and bell of the Kerner horn in the left of Figure 6.9, the 1769 instrument. It is likely that these stays were added at a later date, perhaps after repair work had been carried out; close inspection revealed that at some point in the history of the instrument, the mouthpipe has been reinforced, and there are also repair patches on the bell underneath the stays.

Manufacturing details such as these can not be detected by the comparison software, which is solely concerned with the shape of the bore profile, but the software

might still be able to offer additional insight in this area, in helping to determine whether sections of tubing may have been repaired or replaced. For example, if deviation was shown to occur in a distinct length of tubing between two instruments which were otherwise very similar, this might signify a matter for further investigation, to see whether repair work or alteration might be the cause.

Consistency in manufacture was also observed in instruments of an earlier date than the Kerner horns. The example in Figure 6.10 shows a comparison between two unsigned horns, thought to be made in the early eighteenth century. The

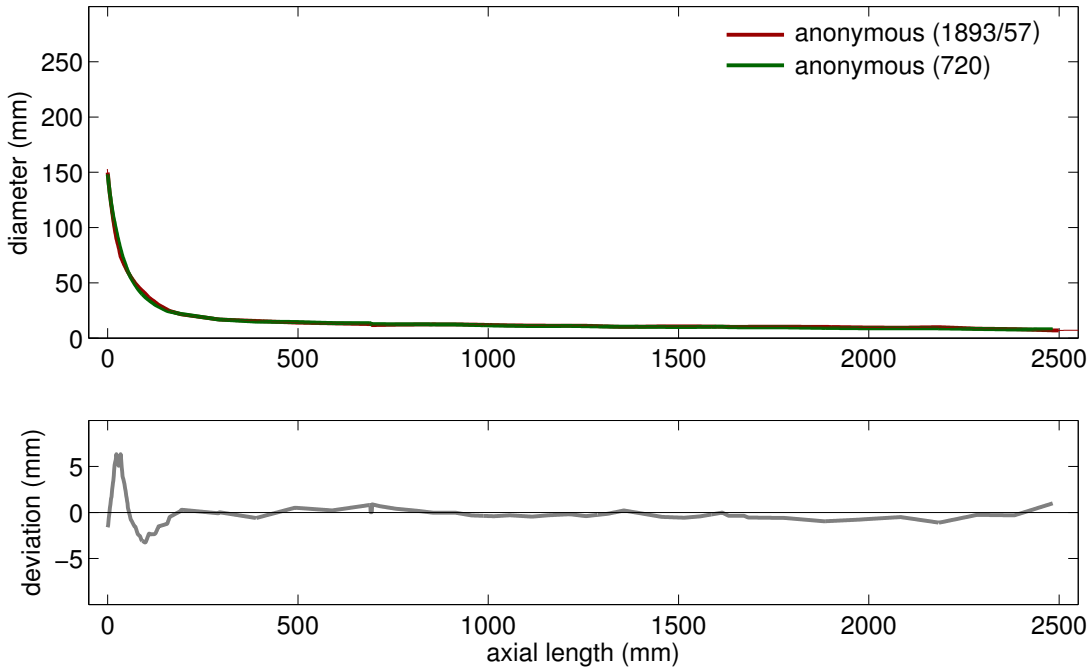


Figure 6.10: Bore profile comparison of two anonymous horns from the early eighteenth century, located in two different collections (D.LU.mk, 1893/57) and (A.W.km, 720). The graph shows that they are a very close match.

anonymous horn (D.LU.mk, 1893/57) is one of a pair of horns from a collection in Lübeck and was initially chosen as the target instrument to run the software on, in order to see how closely it matched its partner (D.LU.mk, 1893/56). The results were slightly surprising because the closest match was found to be, not with its partner but instead, with a different anonymous instrument from a collection in Vienna (A.W.km, 720). The horn from Vienna is also one of a pair of small

baroque horns. Photographs of both pairs of anonymous horns can be seen in Figure 6.11.

When the comparison software was run on all four horns, it was apparent that these instruments all share very similar bore profiles. This gave rise to the possibility that these two pairs of horn might have been made by the same maker and so further investigation was carried out by looking more closely at manufacturing details on the instruments.

Figure 6.12 shows photographs comparing two distinctive parts of the horn: the bell and the joins. On inspection, the instruments were found to share many similarities such as the exact location and type of joins on the corpus, and also of the seams on the bells, but there were also some interesting differences. These included inconsistencies in the markings on the bell garlands and different mouthpipes in both length and detail. The bell stays and ferrule markings appear to be similar but not identical, see Figure 6.12. Despite some of these differences concerning the aesthetic appearance of the horns, their extremely similar bore profiles would seem to suggest that these four instruments were most likely shaped on the same mandrel or at least made to the same design specifications.

Not all brass instrument makers produced instruments with such uniformity in design. There are several horns by the mid-eighteenth-century London maker Winkings which show a much greater variation in design. This variation has already been mentioned with regard to the outline shape of the instruments (see Section 5.2.2, Figure 5.8) but bore profile comparisons also revealed significant differences in the diameter of the tubing, particularly in the region of the bell.

The database of measurements currently includes five different bore profiles of horns by the maker Winkings and the two graphs in Figure 6.13 show an example of a good and a bad match from amongst these five horn profiles (note that the graph showing deviation has not been included). Only the bell flare (approximately the first 250 mm from the end of the bell) was selected for comparison, and the target horn in both cases was the Winkings horn (GB.E.u, 2493) referred to previously in this chapter, see Section 6.2.1.

The results in the top graph show the Winkings horn (GB.E.u, 2493) compared to a

Figure 6.11: Photographs showing two pairs of anonymous horns from the early eighteenth century. Top: pair located in Lübeck (D.LU.mk), left (1893/57), right (1893/56). Bottom: pair located in Vienna (A.W.km), left (720), right (721).

Figure 6.12: Photographs showing similarities and differences between details of the bell stays (top) and joins (bottom) on two of the horns from Figure 6.11. Left: anonymous (D.LU.mk, 1893/57). Right: anonymous (A.W.km, 720).

Winkings horn located in Oxford (GB.O.ub, 604). Apart from a small kink towards the bell rim on the Oxford horn, due to slight denting in this area, the two bell profiles are very similar. The results on the bottom graph however, show two very different bell profiles. In this example, the target horn (red line) is compared to another instrument from the collection in Edinburgh (GB.E.u, 2492). These two bells clearly have a very different shape which would suggest that they might have been made using different mandrels.

Information such as this concerning variation in bell design could be useful for more accurate dating of instruments, and also for exploring the extent to which instrument design varied within a workshop, helping to shed light on early brass instrument manufacturing practices.

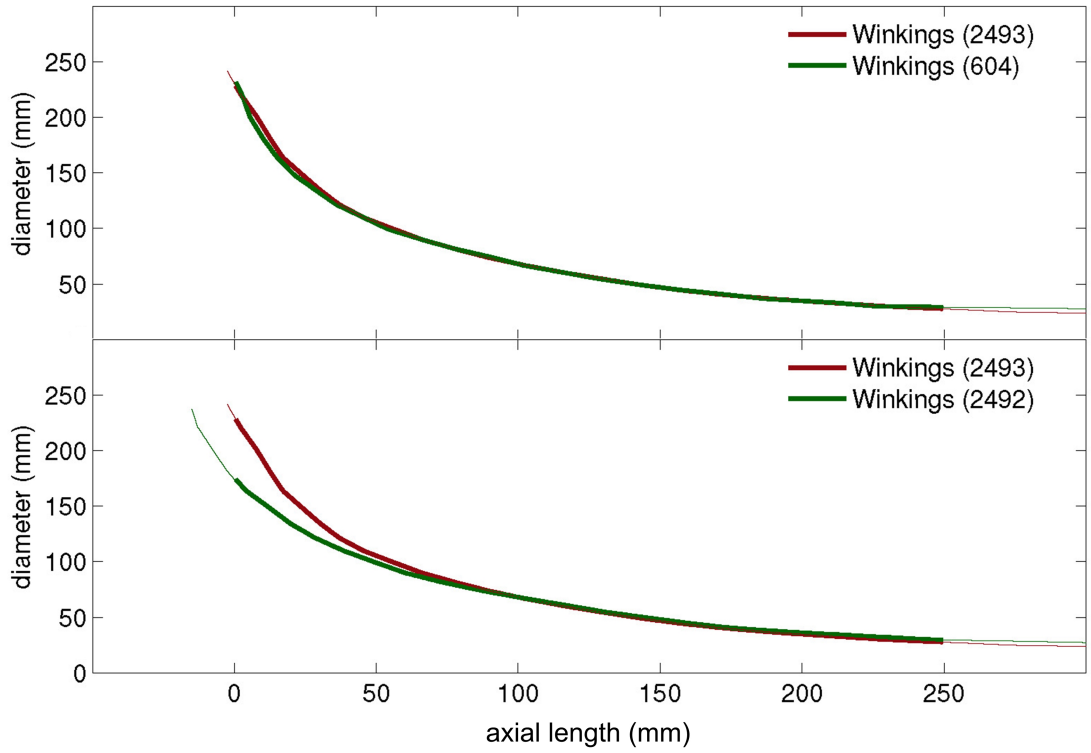


Figure 6.13: Bore profile comparison of horns by the maker Winkings, mid eighteenth century. The target horn in red: Winkings (GB.E.u, 2493). Good match (top) in green: Winkings (GB.O.ub, 604). Bad match (bottom) in green: Winkings (GB.E.u, 2492).

As mentioned previously, the shape of the bore profile is fundamental to the acoustics of a brass instrument and so consistency during the process of shaping the tubing also results in consistency concerning the playing characteristics of the instrument. This can be demonstrated by examining acoustic input impedance curves from horns made by the same maker.

The graph in Figure 6.14 shows two acoustic input impedance curves from a pair of mid-eighteenth century horns by the maker John Christopher Hofmaster (GB.E.u, 3296 and 3297), both measured without the hand in the bell. In order to compare the shape of the graphs more easily, the impedance envelopes have also been included. While it is apparent that these two impedance curves have a similar shape, there are slight differences in the peak amplitudes and perhaps more significantly, there is a difference in pitch of approximately 20 cents.

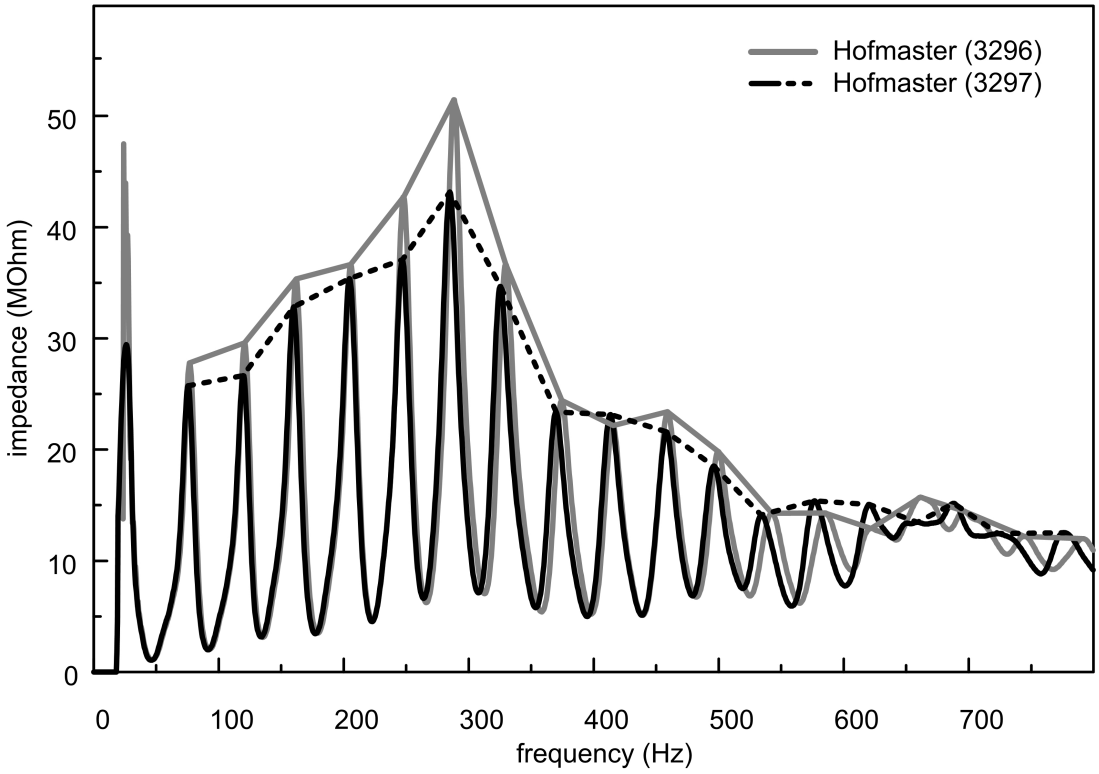


Figure 6.14: Input impedance curve comparison of two horns by the maker John Christopher Hofmaster, from the mid eighteenth century (GB.E.u, 3296 and 3297). The graph shows a similar shape of impedance envelope.

Previously in Section 5.2.2, Figure 5.9, the outlines of three horns by the maker Hofmaster were compared and found to have a reasonably similar wrap, although the bells were at slightly different angles to the mouthpipe. As mentioned previously, the layout of the tubing is of secondary importance concerning the acoustics of the instrument, it is the shape of the air column that matters, and when the bell profiles were compared, these were found to be close match as shown by the graph in Figure 6.15.

Even more similar than the Hofmaster pair, the impedance curves of two anonymous horns (GB.E.u, 2887 and 2888) were found to be almost identical as shown by Figure 6.16. The outlines from this pair of anonymous horns were also discussed in the previous Section 5.2.2, and the results, in Figure 5.10, showed an extremely similar layout of tubing. A bore profile comparison confirmed that they are also a very close match in this respect. Concerning all aspects of their design and manu-

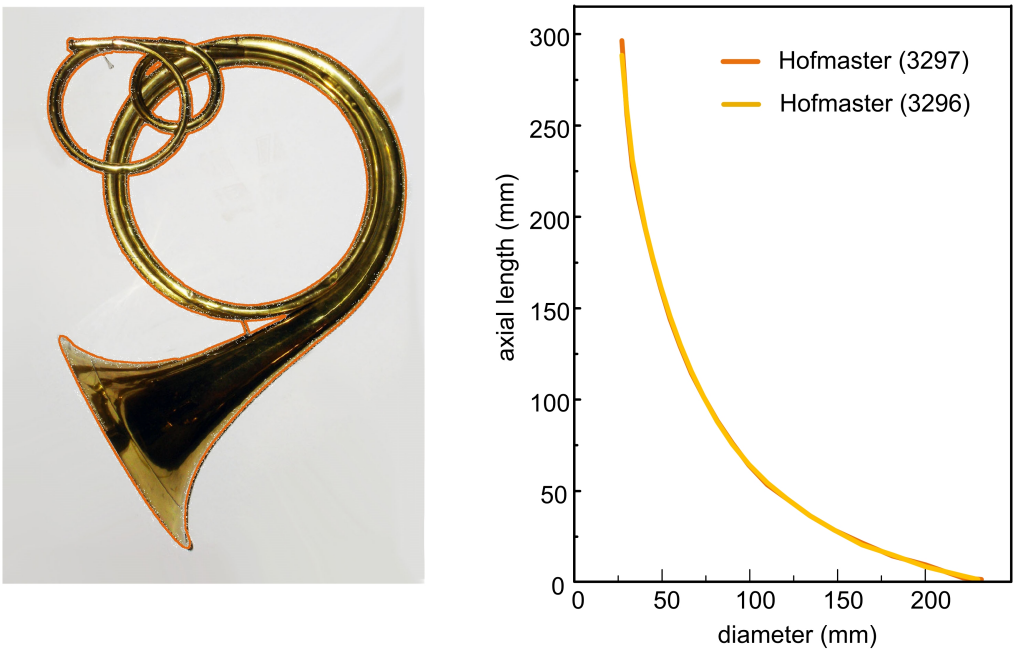


Figure 6.15: Bell profile comparison of two horns by the maker Hofmaster, from the mid eighteenth century (GB.E.u, 3296 and 3297). A photograph of Hofmaster horn (3296) has also been included with the outline shown superimposed.

facture, these two instruments are extremely alike and this is also evident in their shared acoustic characteristics.

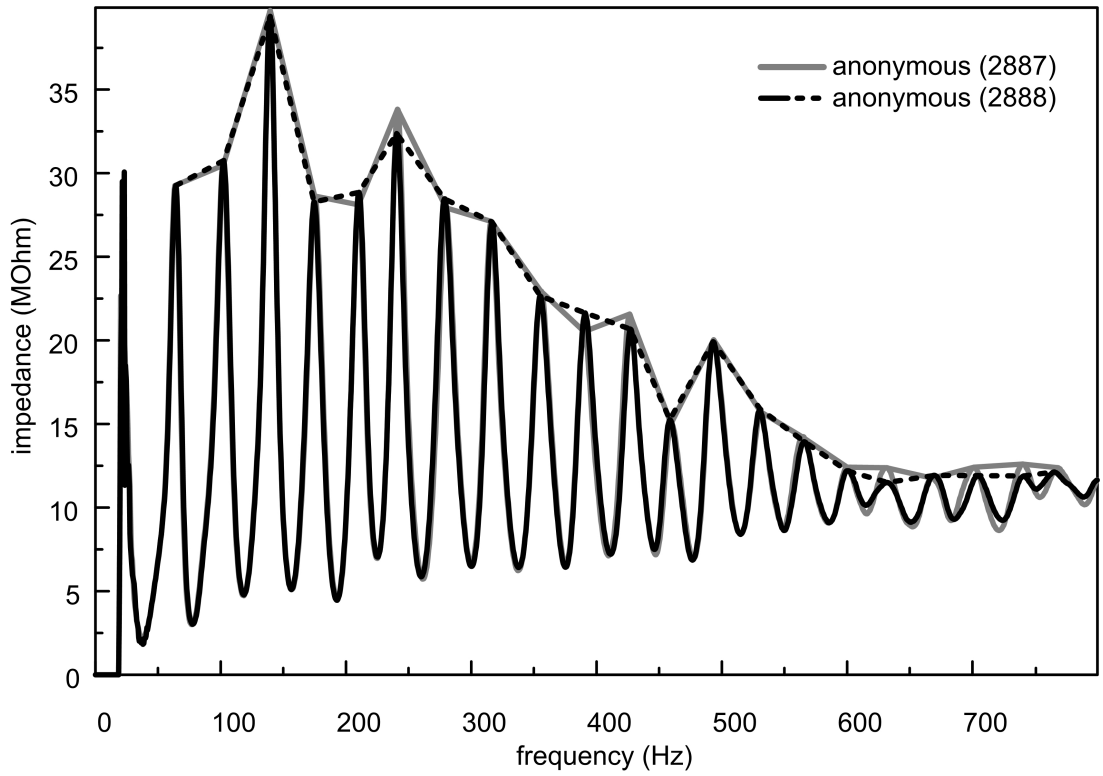


Figure 6.16: Input impedance curve comparison of two anonymous horns from the late eighteenth / early nineteenth century (GB.E.u, 2887 and 2888). The graph shows almost identical impedance curves.

6.3.2 Local variation

Having looked at bore profile variation between instruments by the same maker (previously in Section 6.3.1), these results provided a useful point of reference for examining variation in horn manufacture on a broader scale; how do instruments from different makers vary within one geographical region? The following discussion focusses mainly on early brass instrument makers in England, the majority of which were from London. The comparison of various bore profiles is discussed in the context of manufacturing practices and design preferences.

It is possible that in the early days of brass instrument manufacture, horn makers might have had part of their instruments, such as the bell section, made by a different craftsman unassociated with their own workshop, a practice which is quite common today. Some aspects of brass instrument production, such as making

and shaping a bell, require specialised tools and skills, and so specific instrument parts might have been traded between makers.

The outline comparison on the left in Figure 6.17 shows a distinct similarity in the shape of the bells between instruments by the makers Winkings (red) and Hofmaster (orange), both actively making horns in London around the period of the mid-eighteenth century. The extent of this similarity was confirmed by running

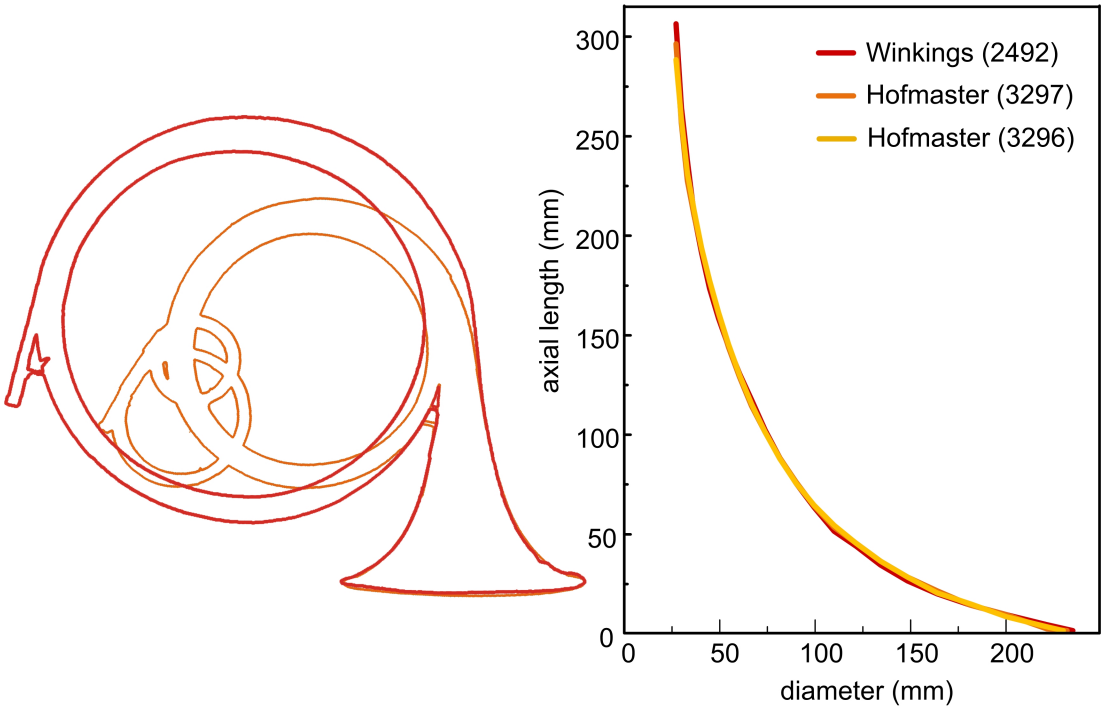


Figure 6.17: Bell profile comparison of horns by the makers Winkings and Hofmaster, from the mid eighteenth century (GB.E.u, 2492, 3297 and 3296). Outline comparison is between a Winkings (2492) (red) and Hofmaster (3297) (orange) horn.

the bore profile comparison software to see how these two horns compared and the results revealed that they were indeed a close match. The bell flares for the Winkings horn (GB.E.u, 2492) compared to two horns by Hofmaster (GB.E.u, 3296 and 3297) can be seen on the right in Figure 6.17.

On initial inspection, a connection between the Hofmaster and Winkings horns might easily have been overlooked due to the very different nature of their respective wraps; the Hofmaster horn has a smaller corpus diameter and was made to be played with a set of crooks, while the Winkings horn is based on an earlier design

with a larger corpus and is fixed pitch. However, after carrying out bore profile analysis, a strong link has been revealed concerning the bell shapes in particular, possibly indicating either use of the same bell mandrel or perhaps shared bell manufacture.

The maker Nicholas Winkings is an interesting individual because, although he is known for his horns made in London, he is originally thought to have come from mainland Europe, most likely Germany given the nature of his name. For this reason it was interesting to run the bore profile comparison software with a Winkings horn as the target profile, in order to see which other instruments would come out as a good match.

Figure 6.18 shows the top three matches after running the comparison software with Winkings (GB.E.u, 2492) as the target bore profile. These three graphs display

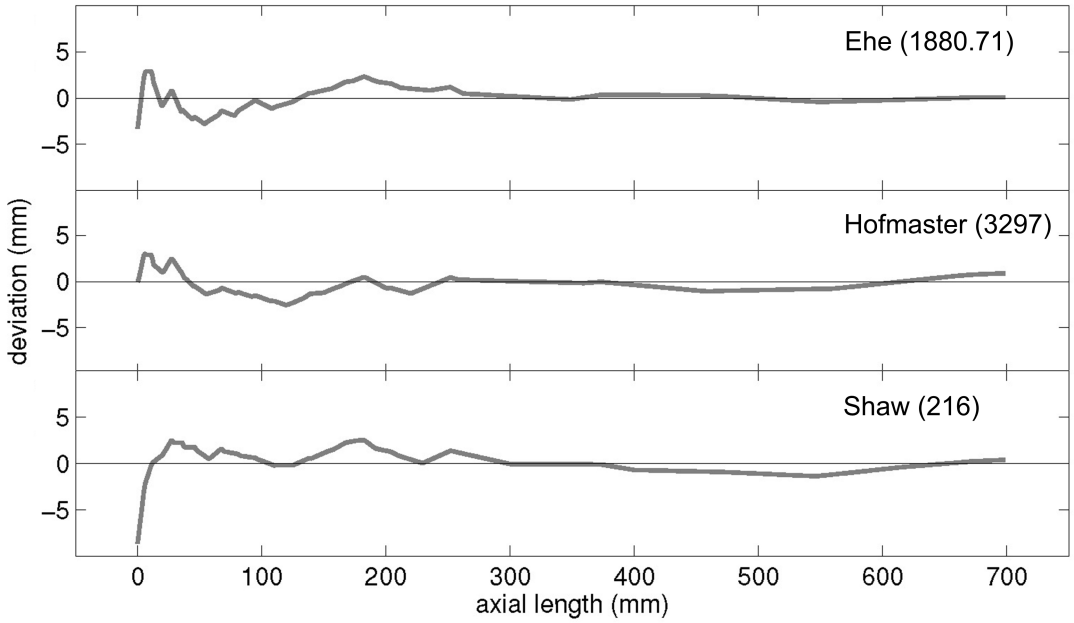


Figure 6.18: Bore profile comparison of the top three matches with Winkings horn (GB.E.u, 2492). Deviation from the target horn is displayed. Top: Ehe (CH.B.hm, 1880.71.). Middle: Hofmaster (GB.E.u, 3297). Bottom: Shaw (A.KR.sk, 216).

only the deviation from the Winkings target horn, the bore profile curves are not included. The part of the horn selected for comparison was the first full section of tubing measured from the bell end before any joins occur, often called the bell

branch, and in this example covers a length of approximately 700 mm. This length is of particular interest because it is the part of the instrument shaped by the bell mandrel as mentioned previously. There is clearly much similarity between the shape of the bore profiles of the four horns compared; Winkings (GB.E.u, 2492) as the target horn, Ehe (CH.B.hm, 1880.71.), Hofmaster (GB.E.u, 3297) and Shaw (A.KR.sk, 216). Greatest variation occurs near the rim of the bell and is jagged in nature, which may partly be explained by a greater incidence of denting in this exposed area compared to the rest of the instrument.

Three of these brass instrument makers were based in London (only Ehe was not making horns in England) and so the similarity of the bore profiles on these horns is perhaps not surprising. Visually, these four horns are quite different as demonstrated by the photographs in Figure 6.19.

The Ehe and Winkings horns (on the left in Figure 6.19) are the most alike within this group, their distinctive wide-coiled corpuses, a characteristic of the hunting horn design. It is estimated that the horn by the German maker Johann Leonhard Ehe was made in the late seventeeth or early eighteenth century, a slightly earlier date than that ascribed to the instrument by Winkings, which is thought be from the mid eighteenth century. Given the possibility that Winkings might originally have come from Germany, his horn design may also have been influenced to some extent by that of German makers, such as Ehe who would have been working in Nuremberg in the early eighteenth century.

The similarity between the Hofmaster and Winkings horns has already been discussed at the beginning of this section, and the results from Figure 6.18 help to put this comparison in the context of other instrument designs.

The close match between a horn by William Shaw and by Winkings is slightly more surprising. Both makers were based in London, but Shaw was making brass instruments at a slightly later date than Winkings, towards the end of the eighteenth century. By this stage in the development of the horn, the tuning slide had become a regular feature of the instrument, and can be seen in the photograph of the horn by Shaw on the bottom right of Figure 6.19. There is also a wider angle between the mouthpipe and the bell when compared to the horn by Hofmaster, perhaps

Figure 6.19: Photographs showing the Winkings horn (GB.E.u, 2492) on the bottom left, with the top three bore profile match horns. Top left: Ehe (CH.B.hm, 1880.71.). Top right: Hofmaster (GB.E.u, 3297). Bottom right: Shaw (A.KR.sk, 216).

to make hand technique slightly easier, a theory supported by ergonomic analysis using the techniques discussed in Section 5.4. Yet despite the slight chronological gap and the significant aesthetic differences, the Winkings and Shaw horns share a very similar bell profile.

Further investigation into the history of Shaw and Winkings in their role as instrument makers, revealed that they both occupied the same address in London

at different stages in their life [Waterhouse, 1993]. The map in Figure 6.20 has been annotated to show the location of this shared address in Holborn (red dot, top right). Also included on this old map of London, dating from 1807, are the

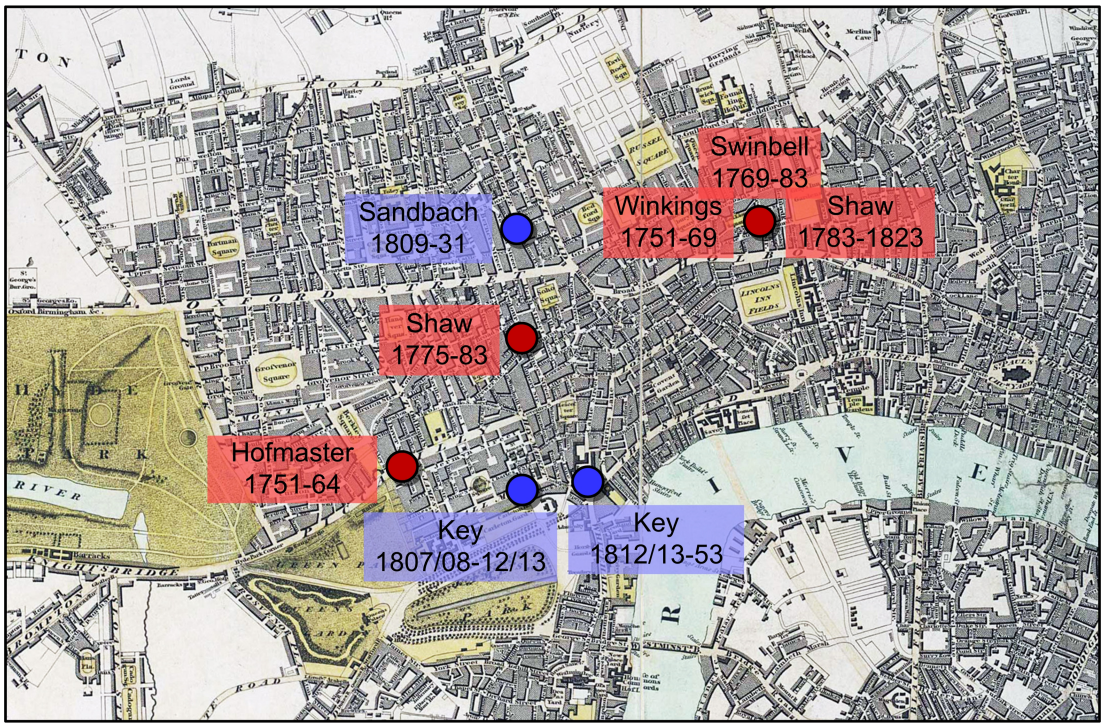


Figure 6.20: An old map of London [Mogg, 1807], showing the locations of several prominent brass instrument makers from the eighteenth (red) and early nineteenth (blue) centuries.

locations of a number of other prominent horn makers from this era, who will be discussed presently.

The address shared at different times by both Winkings and Shaw is 21 Red Lion Street, however Shaw did not immediately supersede Winkings at this address, there was another resident who lived there in between by the name of Swinbell. Not much is known about Swinbell but it it likely that he too was a brass instrument maker given his location and date of residency. If this was the case, it is unfortunate that no instruments have survived to lend credence to this claim. However, it might be supposed that if any horns by Swinbell were to be uncovered, then they too would share a similar bell profile to that of Winkings and Shaw. The reason being that each successive instrument maker would most likely have taken over not just

the premises, but all of the tools and equipment that went with the workshop too, including items such as bell mandrels. Given their expense and difficulty to make, bell mandrels would likely have had their use maximised amongst horn makers, a useful point to consider when trying to identify the origins of anonymous instruments (see Section 6.3.3).

The link between the bore profiles of the Winkings and Hofmaster horns might also be better understood by looking at their places of residence (see map in Figure 6.20). For at least thirteen years of their working lives, their workshops were located approximately one and a half miles apart. On foot this journey from Picadilly, where Hofmaster was working, to Holborn is estimated to have taken less than half an hour. Again it is possible that bell mandrels were shared, or perhaps design specifications. It may even have been the case that one maker supplied the bells for a number of separate workshops in London as is common today.

There are two other brass instrument makers marked on the map in Figure 6.20; Thomas Key and Sandbach, both of whom were making horns at the beginning of the nineteenth century, slightly later than the previous makers discussed. The bore profiles from two instruments by these makers did not result in a top match with the Winkings horn but when compared to each other they were found to have a very similar bell shape.

The outlines from these two horns can be seen superimposed on the left in Figure 6.21 and the detailed bell measurements are shown in the graph on the right. Whilst the bell profiles are clearly very alike, and so too is the corpus diameter, the layout of the tuning slide and of the coiled tubing differs, giving a separate character to both instruments. The diameter of the bell on the Sandbach horn (GB.E.u, 203) is slightly smaller than on the horn by Key (GB.O.ub, 62), but this certainly does not rule out the possibility that these two bells might have been made on the same mandrel. Looking back at the map (Figure 6.20), it can be seen that for over twenty years, Sandbach and Key had workshops that were within about twenty minutes walking distance of each other and so again, it is not surprising that certain aspects of their design are similar.

Running the comparison software on the Sandbach and Key horns also brought to

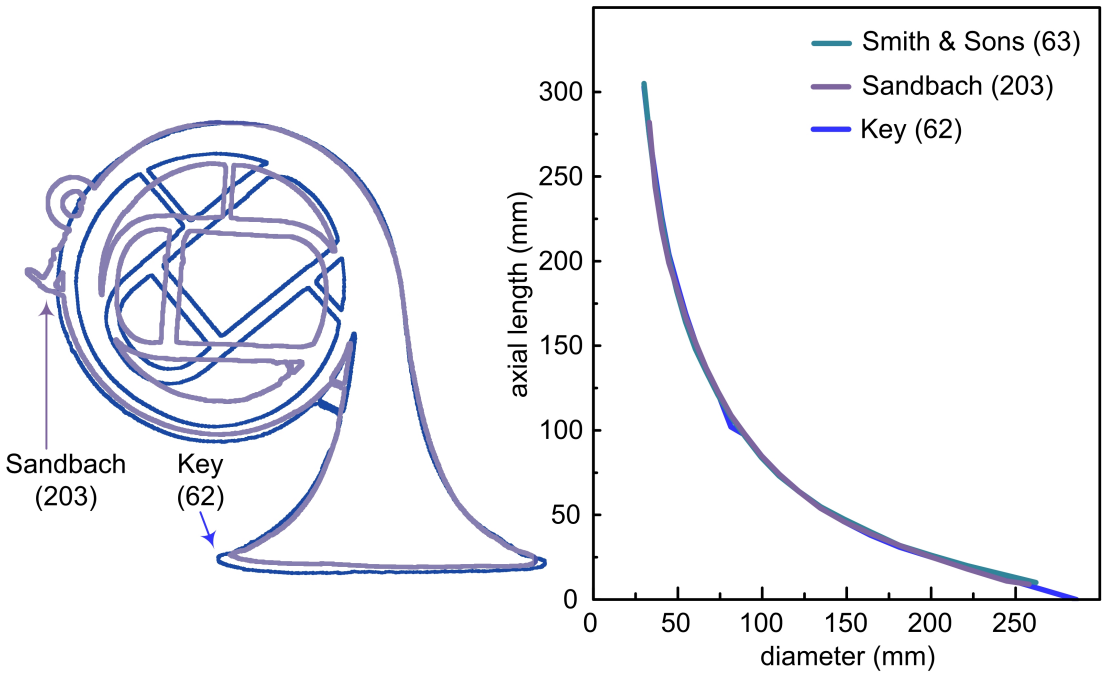


Figure 6.21: Bell profile comparison of horns by the makers Smith & Sons (GB.O.ub, 63), Sandbach (GB.E.u, 203), and Key (GB.O.ub, 62). Outline comparison is between horns by Sanbach (purple) and Key (blue).

light another interesting match, this time with a maker from outside of London; the Wolverhampton firm, Smith & Sons who were making instruments around the same time, the early nineteenth century. The detailed bell profiles for the three horns can be seen on the graph on the right of Figure 6.21 and an outline comparison between Smith & Sons and Key horns can be seen on the left in Figure 6.22. Due to the very different layout of tubing and size of corpus on each horn, the link between these two instruments was only apparent after comparing the bore profiles and outlines, and discovering the similar nature of their bell shapes.

Despite London and Wolverhampton being separated by a distance of over 120 miles, Smith & Sons chose to have some of their instruments transported to London to be sold by Key, as evident by the inscription on the Smith & Sons horn (right of Figure 6.22).

Again, it is only speculation that the bells of these three instruments (by makers Smith & Sons, Sandbach and Key) might have been built by the same craftsman and

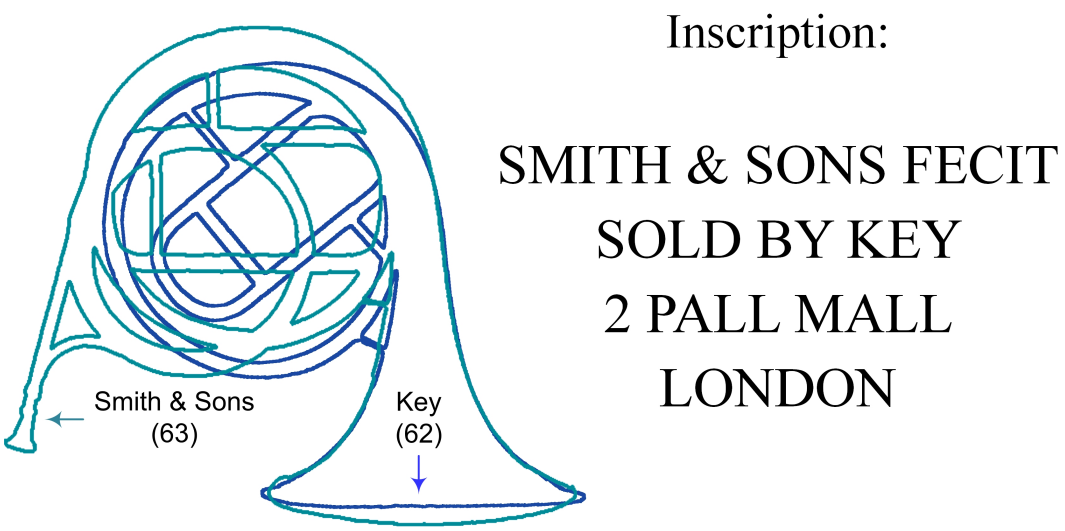


Figure 6.22: Outline comparison is between horns by Smith & Sons (GB.O.ub, 63) and Key (GB.O.ub, 62). Details of the inscription on the Smith & Sons horn (63) is shown on the right, demonstrating a further link between these instrument makers.

on the same mandrel because unfortunately there is little evidence or documentation from this period which might provide further clues as to the manufacturing processes. Nevertheless, it seems possible that there could have been one or a few specialist bell makers, who would have provided the bell sections for a number of different brass instrument makers in London.

The preceding analysis in this section has mainly been divided between horns made in the second half of the eighteenth century and those made at the beginning of the nineteenth century. It is interesting to compare the bell profiles from these two groups to see the extent to which they differ. The graph on the right of Figure 6.23 shows the bell measurements from these two groups and on the left is an outline comparison of a representative horn from both groups.

From the bell profile graph, it can be seen that the main difference between these two groups is that the earlier instruments (red/orange curves) display a more rapid bell flare than those from the early nineteenth century (blue/green curves).

Seen in the context of horn design in general, these differences appear to be relatively small, compared with the larger changes that took place in this era such

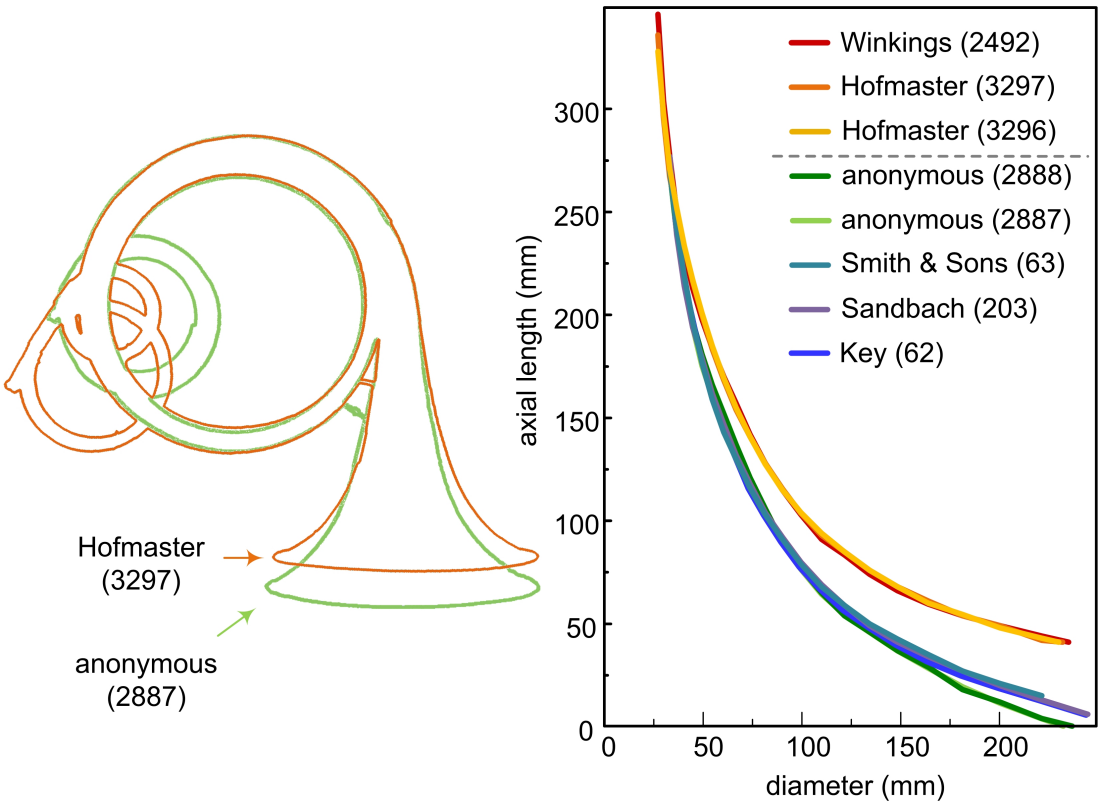


Figure 6.23: Bell profile comparison of horns from the mid eighteenth century (red/orange group) and early nineteenth century (blue/green group). Outline comparison is between a representative from each group; Hofmaster (GB.E.u, 3297) and anonymous (GB.E.u, 2887).

as the reduction in corpus size, the introduction of the crook and coupler system and also of the tuning slide. From an acoustic point of view however, changes in the bore profile, even small variations such as these, play a significant role in influencing, not just the sound of the instrument but also aspects of player response and technique such as ease of playing in the high register and the use of hand in the bell, as discussed previously in Section 4.3.

6.3.3 Identification

Anonymous instruments hold great mystery. The idea for creating this bore profile matching tool was inspired by the desire to find out more about unsigned and

undated instruments. Some of the most common methods of instrument identification include examination of the wrap and of the details on finishes such as ferrules, mouthpipe, stays, bell garland, etc. A less common approach is to analyse the bore profile, perhaps due to the more time consuming nature of its aquisition, although this can be equally as rewarding. A combination of both techniques offers the most thorough investigation from which to draw conclusions.

There are a number of English instruments included in the database of bore profile measurements (many of which are discussed previously in Section 6.3.2), including one anonymous instrument, now housed at the Boston Museum of Fine Art, which is thought to be of English origin (US.B.mfa, 17.2001). The horn has no markings or inscription which might provide clues as to where it was made or the date of manufacture. It does however, bear a close resemblance to a horn by the London maker Shaw (A.KR.sk, 216) which was discussed in the previous section. Photographs of both instruments are displayed in Figure 6.24 for comparison. From these photos, it is clear to see that the two horns share a very similar wrap, including the location and angle of the tuning slide relative to the rest of the instrument, but some of the stays differ slightly in style and location.

They do however, appear to be a close match when analysed using the bore profile matching tool to compare their bell shapes, as evidenced by the graphs in Figure 6.25. Shaw was making horns in the late eighteenth and early nineteenth centuries, and so it is very likely that this anonymous instrument was also made in London at around the same time, probably before the turn of the century because there appears to have been a general change in the shape of horn bells made in London at some point during the early nineteenth century (see Section 6.3.2) and these horn bells conform to the earlier design style.

Another anonymous instrument which holds particular intrigue is a horn (D.LU.mk, 4422) examined at a small collection in Lübeck, Germany, shown in the photograph on the right of Figure 6.26. It is interesting largely because there are not many horns which have survived from the eighteenth century, in such good condition, which use this type of crooking system. The name given to this design of horn is an inventionshorn. It features a type of crook which fits into the middle of the instrument allowing the mouthpipe to be fixed, giving the advantage of greater

stability, particularly when employing hand technique.

A surprising match was revealed after running it through the bore profile comparison software; the top match was with a horn by the maker Christian Gottfried Glier (CH.B.hm, 1980.2039.) which is currently located at the Museum für Musik in Basel. A photograph of this instrument is shown on the left in Figure 6.26 and the results form the bore profile comparison are shown in Figure 6.27. Like some of the examples discussed earlier when examining consistency within one workshop, the two bore profile curves in this example (anonymous and Glier horns) are such a close match that the red line is almost indistinguishable beneath the shape of the green line. The two profiles deviate by less than a few millimetres throughout the section of tubing selected to be displayed, which at 2500 mm is almost the entire length of each instrument.

Figure 6.24: Photographs comparing an anonymous horn on the left (US.B.mfa, 17.2001) to a horn by the maker Shaw on the right (A.KR.sk, 216).

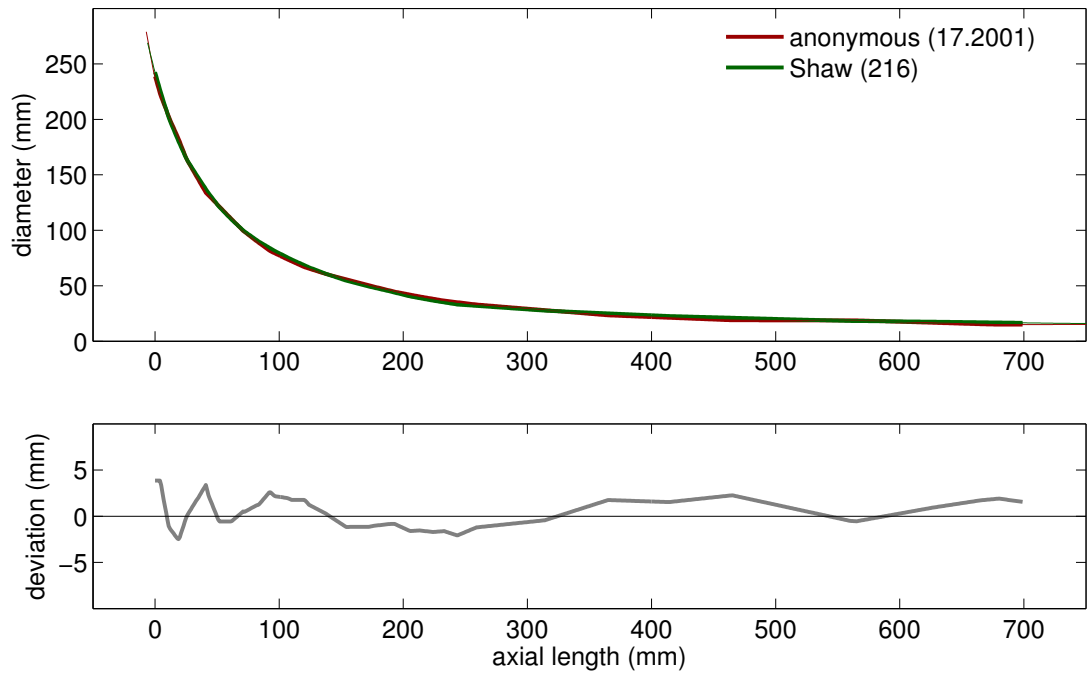


Figure 6.25: Bore profile comparison of an anonymous instrument (US.B.mfa, 17.2001) and a horn by maker Shaw (A.KR.sk, 216) from the late eighteenth century. The graph shows that they are a close match.

Not only did the horn by Glier come out as top match to the anonymous inventionshorn, but the two instruments are distinctive; they share a unique shape of bore profile which no other horns in the database came close to matching. The horns ranked immediately lower in second and third place were significantly different, particularly concerning the shape of the bell flare.

The graph in Figure 6.28 emphasises the difference between the more gradual bell flare on the Glier horn and the anonymous inventionshorn (red and blue lines) compared to the later and more rapid expansion of tubing on an early eighteenth-century anonymous instrument (green line). The main reason that the shape of the matched bell flares is so distinctive, is because there are two gentle but discrete kinks in both bore profiles which can be seen in Figure 6.28 where the bell sections have been magnified. The gentle kinks occur at approximately 25 mm and 100 mm diameters, measured from the end of the bell.

The horn by Glier would not have been an obvious instrument to examine in

Figure 6.26: Photographs comparing an anonymous horn on the right (D.LU.mk, 4422) to a horn by the maker Glier on the left (CH.B.hm, 1980.2039.).

connection with trying to identify the anonymous inventionshorn, because the two instruments are visually very dissimilar indeed, see the photographs in Figure 6.26. There is the obvious difference concerning the wrap of both horns; the Glier horn features a terminal crooking system and has no tuning slide, whereas the anonymous instrument, as mentioned previously demonstrates the inventionshorn crooking system.

There are also differences concerning the finishes on some of the manufacturing details, but it would appear that the Glier horn has undergone some repair work involving the bell stay and the first branch (section of tubing immediately following on from the bell branch). An overlap join is the wrong way round and it is likely that a new replacement bell stay was fitted. Perhaps originally it might have had

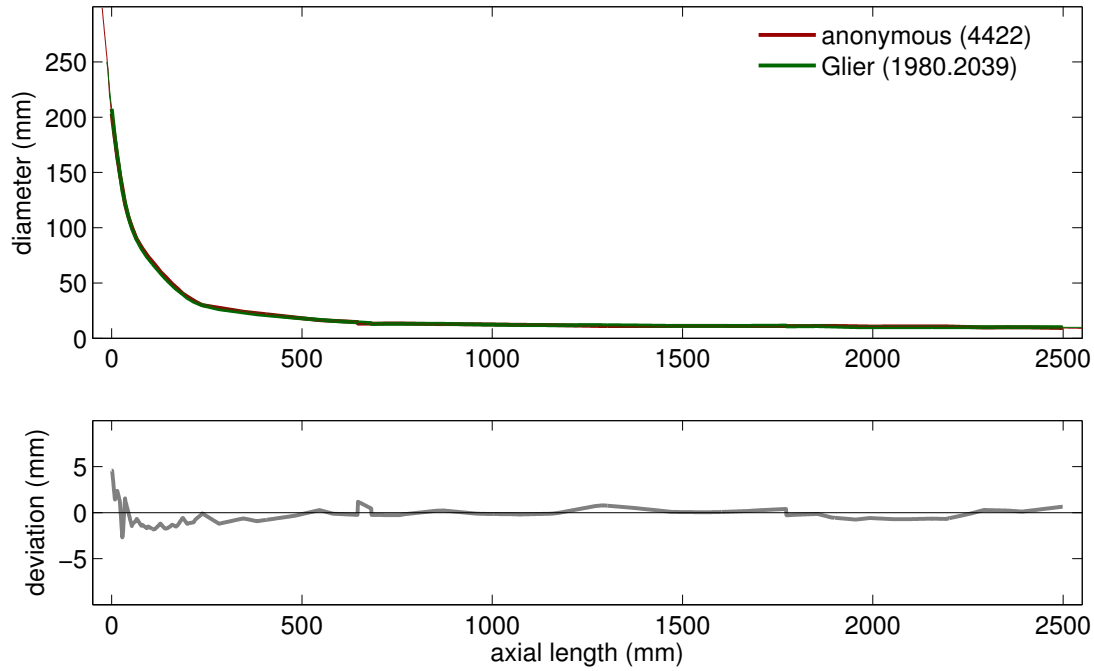


Figure 6.27: Bore profile comparison of an anonymous instrument (D.LU.mk, 4422) and a horn by maker Glier (CH.B.hm, 1980.2039.), dated 1792. The graph shows that they are a very close match.

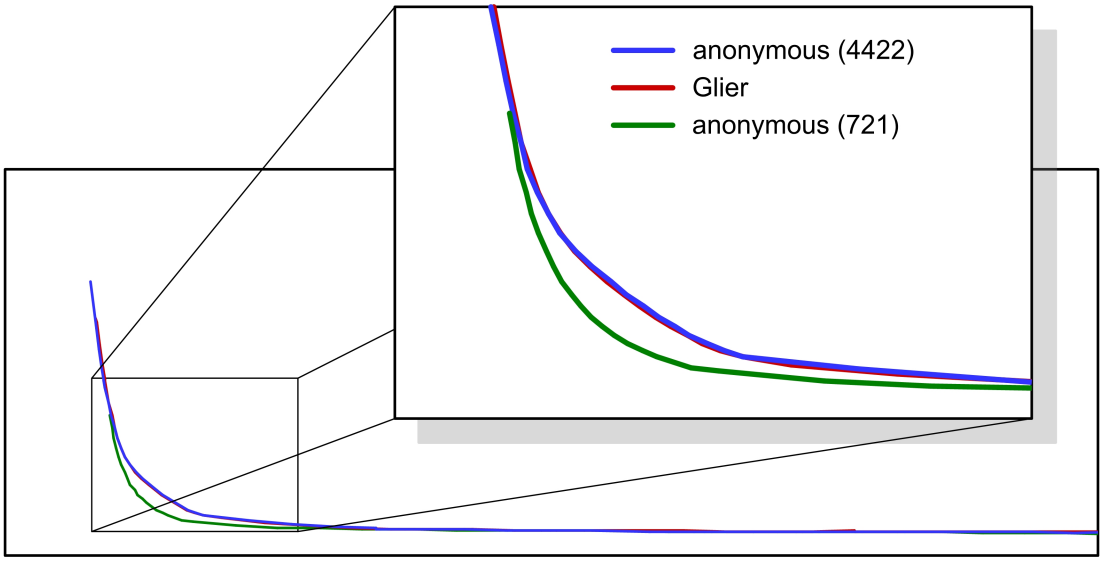


Figure 6.28: Magnified bore profile comparison showing the distinctive bell shape shared by an anonymous instrument (D.LU.mk, 4422) and a horn by maker Glier (CH.B.hm, 1980.2039.). Another anonymous instrument (A.W.km, 721) from the early eighteenth century is also included.

different finishes and manufacturing details.

The bell section is an area where the two instruments are alike, not just in terms of the shape of their profiles, but also with reference to the bell garlands. These are very similar as can be seen in the photographs in Figure 6.29. Both garlands have a distinctive double band engraved and the spacing of this and the width of the garlands is almost identical. The seams and gussets are also very similar and again quite distinctive. The bells do vary in terms of their final diameter, by approximately 50 mm, but given the similar shape of their bell profiles, this does not rule out the possibility that these two bells might have been made on the same mandrel. Decisions about the final size of the bell diameter on a horn are independent to the shaping of the bell on the mandrel.

Although these two horns are now located in collections in different countries, Germany and Switzerland, the possibility can not be ruled out that these instruments might share a bell profile shape because at some stage in their more recent history they were repaired on the same bell mandrel. However, it should be noted that the close match is not only confined to the shape of the bell, but also to the tubing along most of the length of both instruments, and so this uniquely shared profile is most likely a signifier that these horns also have a shared origin.

Figure 6.29: Photographs showing the similarities between garland details on an anonymous horn (D.LU.mk, 4422) (bottom) and a horn by the maker Glier (CH.B.hm, 1980.2039.) (top).

6.3.4 Irregularities

This final example of a use for the bore profile comparison software involves the detection of irregularities in the shape of a profile. The graphs in Figure 6.30 show the output results after comparing two different horns by the maker Eichentopf from collections in Basel (CH.B.hm, 1980.2134.) and Prague (CZ.P.nm, E 85) and finding interesting differences in the shape and location of joins in the tubing. The

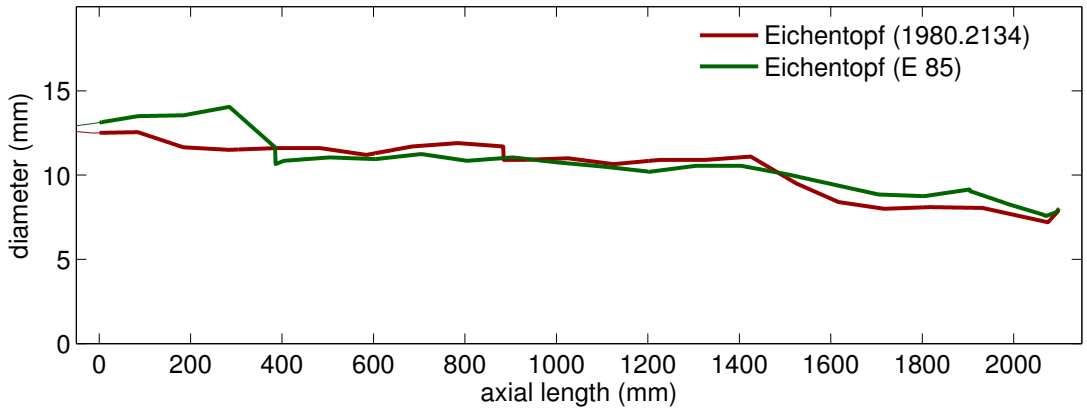


Figure 6.30: Bore profile comparison showing irregularities in the tubing between two horns by the maker Eichentopf, dated 1735. Horn located in Basel (CH.B.hm, 1980.2134.) in red. Horn located in Prague (CZ.P.nm, E 85) in green.

part of the bore selected for comparison in this example was approximately the first 2000 mm from the start of the mouthpipe, which accounts for the majority of narrow tubing on these instruments.

This section was chosen because when measuring the Eichentopf horn located in Basel (1980.2134.), it was apparent that some repair work had been carried out, examples of which can be seen in the photographs in Figure 6.31. Points of weakness such as the joins between sections of tubing shown here are more susceptible to damage and cracking. Subsequently leaks can occur which become apparent when attempting to play the instrument, resulting in an unfocused tone quality.

In order to assess the playing characteristics of this instrument and to see if any leaks could be detected in the tubing, acoustic impedance measurements were

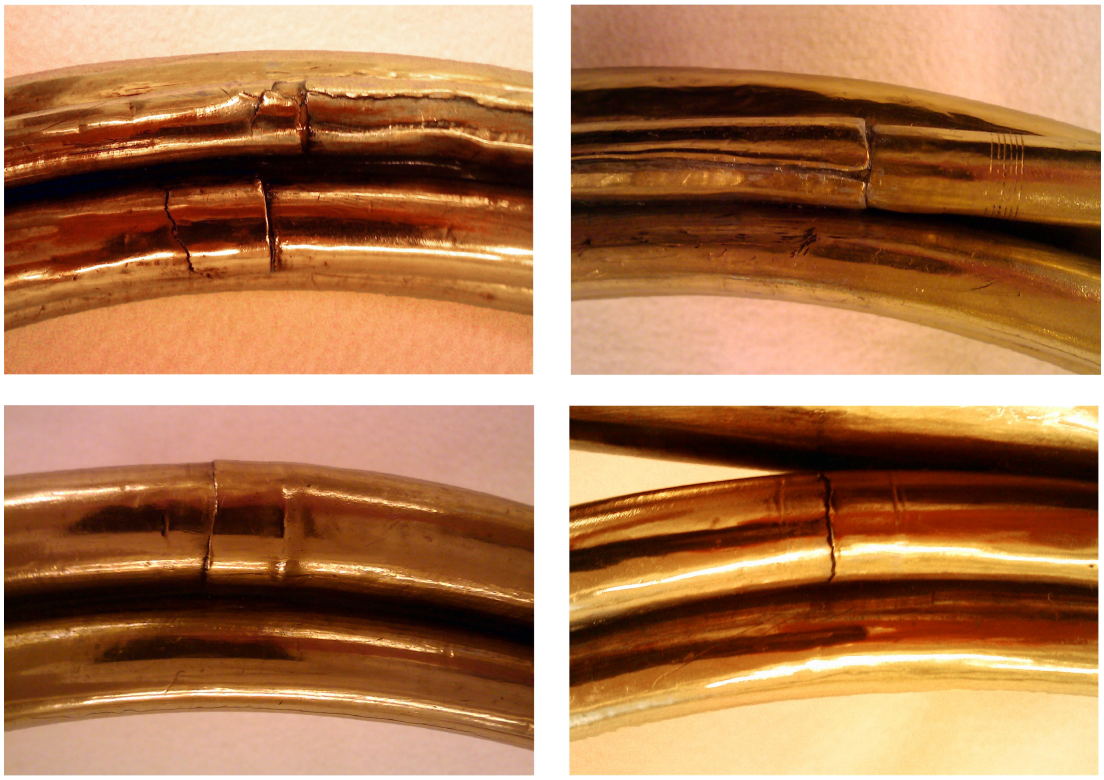


Figure 6.31: Photographs showing details of damaged and repaired joins on a horn by Eichentopf (CH.B.hm, 1980.2134.).

taken and the results are displayed in Figure 6.32. The graph shows an atypical acoustic response, characterised by an unusually undulating envelope curve. An uneven impedance measurement shaped such as this would suggest an unfavourable acoustic response when playing the instrument. Initial thoughts when analysing this graph involved speculation as to whether there might be a leak or even a foreign body lodged inside the tubing, given the damage evident at the join locations.

In order to explore this area still further, computational modelling was carried out which was able to predict the acoustic impedance of the horn (without the hand in the bell) using detailed bore profile measurements as the input. This proved to be very useful as a comparison to the measured impedance data. Further information about the model can be found in Section 6.2.2. In Figure 6.32, both the measured and the modelled acoustic impedance results are displayed on the graph. Surprisingly, the curves were found to be very similar, with both results

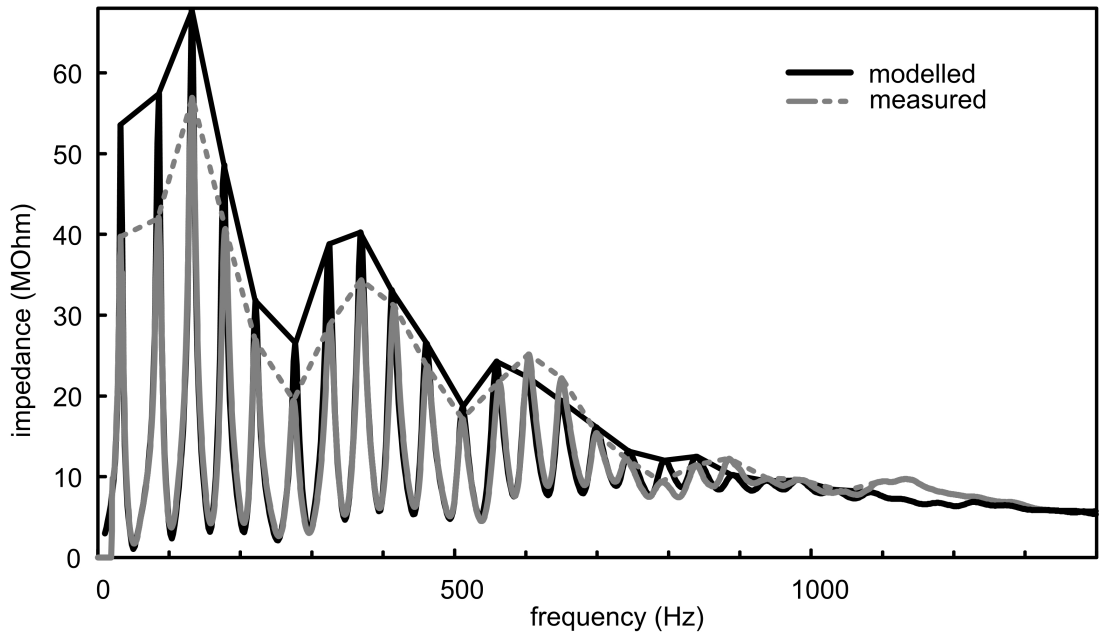


Figure 6.32: Input impedance curve comparison of measured (black line) and modelled (grey line) results from a horn by the maker Eichentopf, dated 1735 (CH.B.hm, 1980.2134.). The graph shows similar shapes of impedance envelope.

demonstrating the characteristic undulating envelope shape, which would imply that the internal surface of the tubing was in good condition and that there were no unexpected energy losses. This similarity between modelled and measured impedance is also extremely encouraging as it demonstrates the potential of this technique for predicting the acoustic response of instruments which are no longer in playing condition.

Turning back to the shape of the bore profile for further clues as to the cause of this unusual impedance curve, the graph in Figure 6.33 shows the initial 2000 mm of tubing on the Eichentopf horn (1980.2134.), measured from the mouthpiece receiver. At about 500 mm in from the start of the mouthpipe (approximately 3000 mm on the graph as measured from the bell), there is quite a sudden flared expansion and then a step occurs about 700 mm later (approximately 2300 mm on the graph), after which the tubing becomes narrower again; these are relatively dramatic changes to occur in the initial section of a brass instrument and they are likely to have contributed to the unusual shape of the impedance curve.

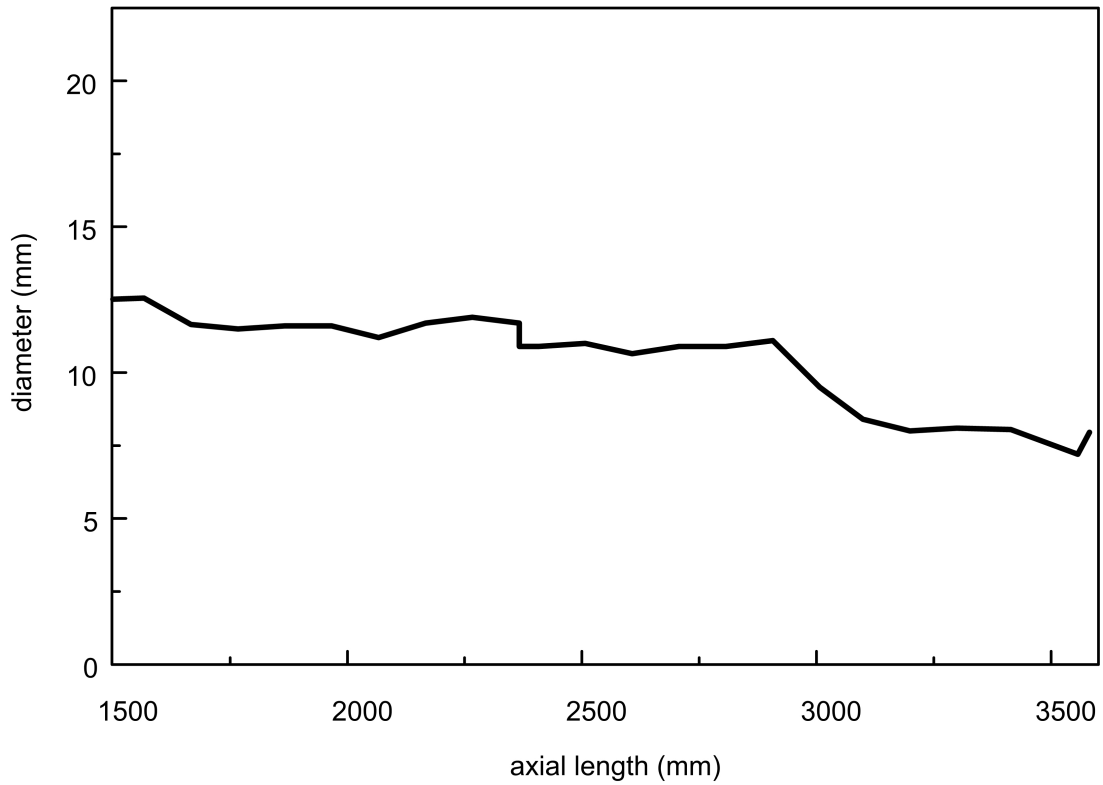


Figure 6.33: Bore profile showing irregularities in the narrower tubing of a horn by the maker Eichentopf, dated 1735 (CH.B.hm, 1980.2134.).

Referring back to the initial output from the bore profile comparison software (Figure 6.30), the other Eichentopf horn (E 85) that was included in the analysis has a bore profile with a more gradual expansion of tubing over the same range, without any major changes in diameter. It is uncertain whether the Eichentopf (1980.2134.) bore profile would originally have followed the shape in Figure 6.33 or whether this is the result of one or more repairs over the course of its history. Analysis of the acoustic impedance which was carried out would perhaps suggest that this was not the original intended shape of the instrument and that the more gradual expansion, as demonstrated by the comparison Eichentopf horn (E 85), might be closer to its original form.

6.4 Conclusions

The importance of bore profile analysis as a tool for identifying and exploring the history of eighteenth-century horns has been demonstrated in this chapter through the discussion of specific examples of bore profile comparisons looking at areas such as consistency in manufacture, variation between instrument makers, identification of anonymous instruments and identification of potential repairs and adaptations to the instrument. Most of the ideas discussed were based on the assumption that sections of tubing would have been shaped on mandrels, thus providing a distinctive feature of design which might highlight possible links between instruments with similar shaped tubing.

The difference in bore profile between two instruments is difficult to detect based on initial visual inspection and this problem increases the greater the number of instruments being compared. A solution was found through the use of a piece of software which was created with the capacity to analyse a large database of bore profile measurements within a few seconds and provide examples and details of similar matches. By using this software tool, the time taken to analyse instruments was reduced dramatically.

The examples discussed in this chapter were limited to the study of early horns, but the bore profile comparison software has the potential to be useful more generally as a tool for exploring brass instrument categorisation. For this to happen, the database of bore profile measurements would need to be extended to include many more different types of brass instrument.

Computational modelling was included in the final bore profile comparison example and it is an area which has not yet been fully exploited in the field of early instrument research. It was shown to be useful for providing additional information about instruments with seemingly irregular bore profiles and acoustical measurements, but it also has the potential to provide useful information when exploring the acoustical response of damaged instruments and those no longer in playing condition.

Chapter 7

Final conclusions

7.1 Aim

The aim of this thesis has been to explore the development of the horn in the eighteenth century in order to find out more about variation in the design of the instrument and about how it might have been played. This is an area of particular interest to modern players of the early horn looking to make informed decisions about the type of instrument and about a suitable playing technique which might be appropriate for a certain piece of repertoire, or to the museum curator wishing to identify an anonymous instrument.

There are many unanswered questions relating to the horn and horn playing in this era, particularly concerning the issue of hand technique, but previous research has mainly drawn on archival evidence to form the basis for conclusions. However, there is a great deal of potential information provided by original historic instruments, which has not yet fully been exploited by researchers.

Instrument-based research has been at the core of this investigation although the findings from archive-based research have also been considered. Data collection has mainly involved measuring the bore profile of each horn, recording details of the wrap, and taking acoustic measurements. Interpretation of this data was

carried out by approaching the topic from a number of different multi-disciplinary angles, employing analytical techniques used in fields such as musical acoustics, ergonomics and design.

Each of the results chapters were based on a different approach to instrument analysis and the main findings in each area were summarised at the end of the chapter along with suggestions for future work in the specific field. These included analysis of timbral variation in Chapter 3 on **sound** (conclusions in Section 3.5), analysis of acoustic response in Chapter 4 on player **technique** (conclusions in Section 4.4), analysis of ease of playing with the hand in the bell in Chapter 5 on **ergonomics and design** (conclusions in Section 5.5), and finally an analysis of manufacturing trends in Chapter 6 on **bore profiles** (conclusions in Section 6.4).

The following discussion in the rest of this chapter will form an assessment of the contribution of each of these areas to the questions raised at the start of this thesis. There will be a particular emphasis on how the results from these disparate investigative paths can be brought together to bring greater understanding to this area of historic instrument research. Finally, the last section will look ahead to the new possibilities for further research which follow on from, and have been inspired by, the findings in this thesis.

7.2 Various approaches

The uncertainty surrounding eighteenth-century horn technique has been a recurring topic of discussion throughout this thesis. In the past, researchers have mainly based their assumptions about when hand technique was first introduced, on a secondary recounting of the story that Hampel 'discovered' the technique. This anecdote appears in an early nineteenth-century horn method by Domnich [1807] and subsequent horn historians have cited this source, suggesting that the introduction of hand technique occurred around the middle of the eighteenth century.

More recently, scholars such as Hiebert [1992; 2006] have turned to manuscripts

and music to search for clues about hand technique and have concluded that players were most likely experimenting with the hand in the bell at an earlier date than previously thought; the most likely setting for such experimentation being the innovative and pioneering musical scene at the court of Dresden. The research from this thesis is largely in agreement with the latter viewpoint, and suggests that some form of hand technique may have been employed as early as the beginning of the eighteenth century. However, the findings also suggest, perhaps not surprisingly, that hand technique would most likely have become established at slightly different times and rates in the various regions and cities across Europe.

An ergonomic approach to the question of hand technique was found to be particularly revealing. The ergonomic diagram used in the analysis made it easy to see which horns might potentially be comfortable to play with the hand in the bell and the results indicated that a number of early eighteenth-century instruments from Germany were of a design which matched this ergonomic concept. It may never be known exactly when hand technique first become established, but this research shows that the design of early German horns is such that it would have been very easy for players to experiment with the effect of the hand in the bell on these early instruments, and given the inherently inquisitive nature of human beings, it is also very likely that the hand was being employed within the bell from this early period.

There are very few surviving examples of horns from England around the period of the early eighteenth century and so it was not possible to make assumptions about the emergence of hand technique in England based on these instruments alone. However, ergonomic analysis of instruments from a slightly later period showed that there was a distinct difference in the design of crooked English horns from the mid to late eighteenth century compared to those from elsewhere.

One of the ergonomic implications of this specifically English design characteristic was found to be a slightly more cramped and potentially more uncomfortable hand position, on the assumption that hand technique was employed on these instruments. On the other hand, the English horns feature a different crooking system which may account for this design variation to some extent, but it is also the case that some aspects of this crooking system are not particularly suited to the

demands of playing with the hand in the bell. Based on analysis of the design of horns from England, it is suggested that perhaps players in England adopted hand technique at a slightly later date than their German counterparts.

Another approach which was found to be useful when considering the issue of hand technique, was the analysis of acoustic impedance measurements. Similarly to the ergonomic analysis, an acoustic investigation is not able to provide definite answers concerning player technique, but the results were found to be useful for exploring how horn design has adapted to the adoption of hand technique. The positive effect of the hand in the bell on the acoustic response in the high register was generally found to be less influential on early horns than on those from later in the period. Based on these findings, a ranking system was created which showed that the change in this aspect of the acoustics of the horn followed an approximately chronological trend, directly related to the effects of playing in the high register with the hand in the bell.

With regard to the question of hand technique, the advantage of this method of acoustic research was mainly found to be identifying which horns might have been difficult to play *without* the aid of the hand in the bell, rather than trying to determine those which might have been played *with* hand technique. This is because the first horns which were played with the hand in the bell were probably not intended for such use, and would have been designed to have acoustic properties suited to their intended purpose. Instrument makers would then have responded to the new demands of hand technique, and adapted the design of their horns gradually through a process of trial and error. This type of acoustic analysis is therefore more useful for placing instruments in context and looking for general trends across many horns. The consideration of individual cases is perhaps most useful when cross-referenced and used in conjunction with ergonomic analysis in order to provide additional information about how the instrument might respond to the use of the hand in the bell.

The aim of investigating variation in the design of the eighteenth-century horn has already been covered to some extent in the discussion on player technique, but another method for mapping the development of the instrument was also explored. Acoustic analysis of the change in tone quality was found to be an interesting way

of observing variation in the timbral characteristics of horns since the beginning of the eighteenth century. In general, horns from the baroque and early classical eras tended to show a greater potential for brassiness with increasing dynamic level than horns from later periods. These varying tonal characteristics are largely determined by the shape of the air column, or bore profile, with earlier horns generally featuring a narrower bore profile than later horns.

A number of factors may have influenced these tonal developments; the role of the horn changed significantly at the beginning of the eighteenth century as it came to be associated more with art music rather than its previous role, primarily as a signalling instrument in the hunt. The sound of the horn was no longer required to be strident in order to carry well in an outdoor setting, and this may partly explain the development and the desire for a more mellow tone quality as it moved into the concert hall.

The style of music written for the horn also changed over the course of the eighteenth century with baroque horn players required to have greater facility in the high range of the instrument than musicians active later in the century. The typically narrower and more cylindrical shape of early horn bore profiles, featuring a later but more rapidly expanding bell flare, resulted in an instrument which is generally more suited to playing in the high register, but as hand technique became more widely used the flare on the horn bell was adapted to accommodate the hand more comfortably and the acoustics of the instrument changed. With the adoption of this new technique, composer were no longer restricted to writing in the high register of the horn in order maximise melodic potential; the effect of the hand had opened up many more possibilities, both technically and tonally.

Due to the fundamental nature of the bore profile in affecting all aspects of the acoustics and the practicalities of playing the horn, including not just what it sounds like, but also how it responds to hand and lipping techniques, a thorough investigation into the changing shape of the horn bore profile was presented in the final results chapter, integrating aspects of analysis from the previous three chapters in order to gain a wider understanding of the development and manufacture of the horn in the eighteenth century. The conclusions based on this multi-dimensional approach are discussed in the next section.

7.3 Integration

Chapter 6 on the subject of bore profiles, investigated the manufacture of horns in the eighteenth century, drawing on analysis techniques used in the previous chapters to demonstrate the advantages of an integrated approach to early instrument research. Examples of interesting bore profile comparisons provided the basis for further discussion on all aspects of horn design and acoustics. Some of the findings included the discovery that a number of English horns from the eighteenth and early nineteenth century share very similar bell profiles, most likely indicating either the use of a shared mandrel or perhaps a specialist bell supplier. Systematic bore profile matching was also found to be useful for helping to identify anonymous instruments and for detecting irregularities in the shape of tubing on an instrument, indicating that alterations or repair work may possibly have been carried out.

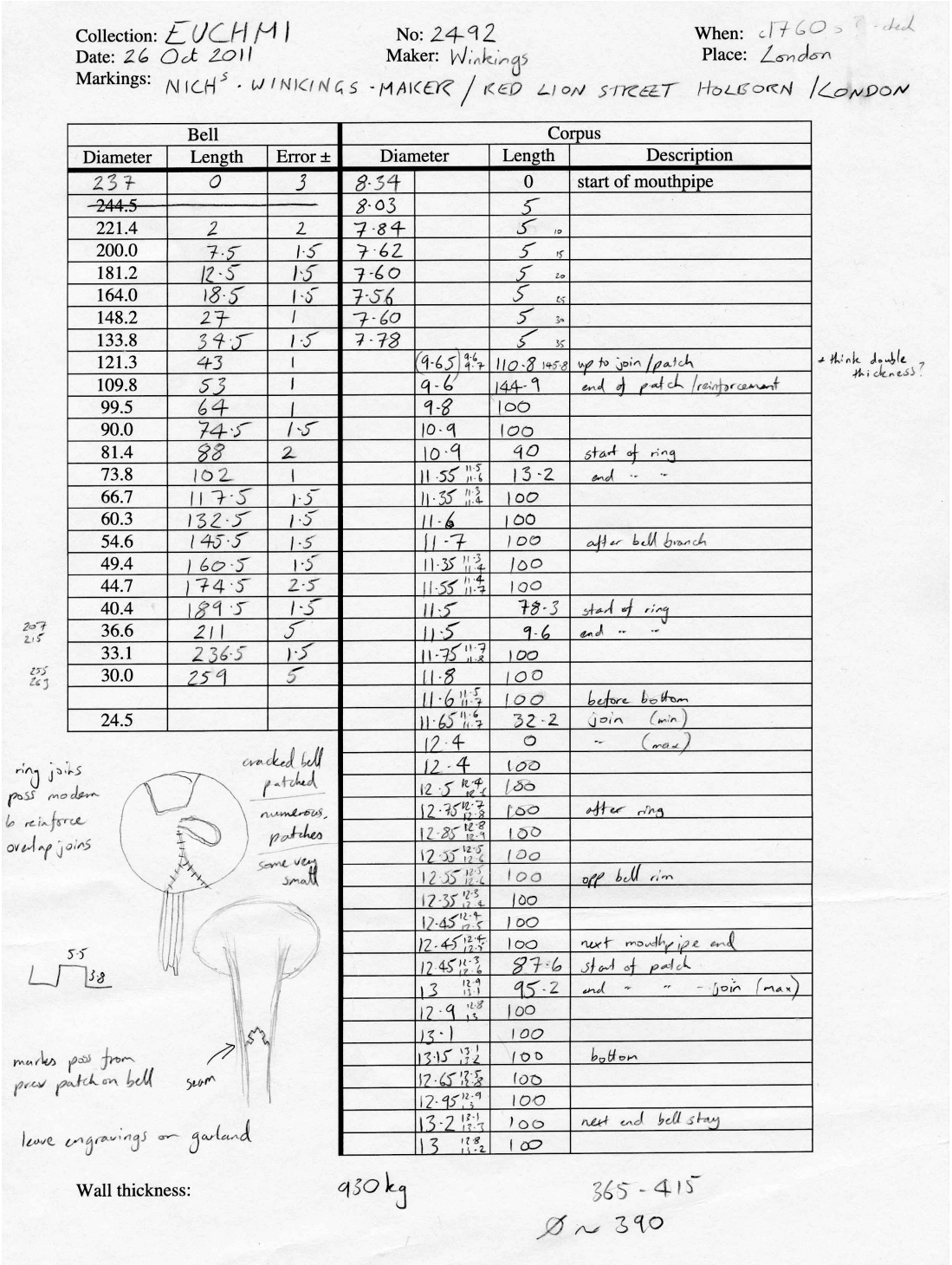
If any of the pairs or groups of horns discussed were to have been analysed in isolation, it would have been extremely difficult to draw any reasoned conclusions from the limited data. However, the strength of this research is partly due to the large number of horns included in the dataset, and partly to the integrated approach to analysis which involves all of the interrelated aspects of instrument design. Referring back to a design principle mentioned in Chapter 5 the phrase, 'form follows function' has a lot to offer the retrospective study of historic horn design.

These discussions and conclusions about player technique may help to provide practical information to horn players interested in historically informed performance practice. This research has highlighted the great diversity of horn design in the eighteenth century in the context of significant changes relating to player technique. It is therefore evident that there can be no set rule as to the type of horn required for a particular piece of music, nor the technique used to play it. The same piece of music might have sounded very different, depending on the country, the setting, and the era in which it was performed. Not to mention the particular preferences of the players at the time for a specific type of instrument or manner of playing, in this extremely diverse musical period. Instead, this information can

be used to help musicians make informed decisions about the types of instrument which might be suitable for a particular performance, depending on their own preferences and those of the orchestra or conductor.

Instrument makers may find value in this type of research when looking to create a copy of a typical horn from a certain period or country. These findings may also provide a useful comparison tool for exploring the differences between an original and a copy. In these cases, data sheets might be helpful, containing all of the relevant information about a particular instrument. The example in Figure 7.1 shows a rough draft of the physical measurements and observations on a horn by Nicholas Winkings (GB.E.u, 2492). The example in Figure 7.2 provides information about the acoustics and design of this horn. Information such as this might also be of value to museum curators looking to build up a full and detailed picture of a particular instrument.

Another way in which this research can be of benefit, is in providing a frame of reference when trying to find out more about an individual instrument, whether this be how the shape of a particular horn fits with others from the period in which it was made, how ergonomically suited it might be to hand technique, or if it has any unusual acoustic properties. In the case of unsigned instruments, this information might also help to narrow down a possible date of manufacture and place of origin. This multi-dimensional approach to the study of the historic horn provides a framework to enable researchers to draw their own conclusions about how an individual instrument might fit, in the context of trends in the development of the eighteenth-century horn in general.



Collection: EUCHMI No: 2492 When: c1760 > ? - ded
Date: 26 Oct 2011 Maker: Winkings Place: London
Markings: NICH^{S} · WINKINGS · MAKER / RED LION STREET HOLBORN / LONDON

Bell			Corpus		
Diameter	Length	Error ±	Diameter	Length	Description
237	0	3	8·34	0	start of mouthpipe
~~244.5~~			8·03	5	
221.4	2	2	7·84	5	
200.0	7·5	1·5	7·62	5	
181.2	12·5	1·5	7·60	5	
164.0	18·5	1·5	7·56	5	
148.2	27	1	7·60	5	
133.8	34·5	1·5	7·78	5	
121.3	43	1	(9·65) 9·6 9·7	110·8 145·8	up to join / patch
109.8	53	1	9·6	144·9	end of patch / reinforcement
99.5	64	1	9·8	100	
90.0	74·5	1·5	10·9	100	
81.4	88	2	10·9	90	start of ring
73.8	102	1	11·55 11·5 11·6	13·2	end " "
66.7	117·5	1·5	11·35 11·3 11·4	100	
60.3	132·5	1·5	11·6	100	
54.6	145·5	1·5	11·7	100	after bell branch
49.4	160·5	1·5	11·35 11·3 11·4	100	
44.7	174·5	2·5	11·55 11·4 11·7	100	
40.4	189·5	1·5	11·5	78·3	start of ring
207 215 36.6	211	5	11·5	9·6	end " "
33.1	236·5	1·5	11·75 11·7 11·8	100	
255 269 30.0	259	5	11·8	100	
			11·6 11·5 11·7	100	before bottom
24.5			11·65 11·6 11·7	32·2	join (min)
			12·4	0	" (max)
			12·4	100	
			12·5 12·4 12·6	100	
			12·75 12·7 12·8	100	after ring
			12·85 12·8 12·9	100	
			12·55 12·5 12·6	100	
			12·55 12·5 12·6	100	off bell rim
			12·35 12·3 12·4	100	
			12·45 12·4 12·5	100	
			12·45 12·4 12·5	100	next mouthpipe end
			12·45 12·3 12·6	87·6	start of patch
			13 12·9 13·1	95·2	end " " join (max)
			12·9 12·8 13	100	
			13·1	100	
			13·15 13·1 13·2	100	bottom
			12·65 12·5 12·8	100	
			12·95 12·9 13	100	
			13·2 13·1 13·3	100	next end bell starg
			13 12·8 13·2	100	

* think double thickness?

ring joins post modern to reinforce overlap joins

cracked bell patched

numerous patches some very small

5·5 38

marks post from prev patch on bell

seam

leave engravings on garland

Wall thickness:

930 kg

365 - 415

Ø ~ 390

Figure 7.1: Data sheet showing physical measurements and observations on a horn by Winkings (GB.E.u, 2492).

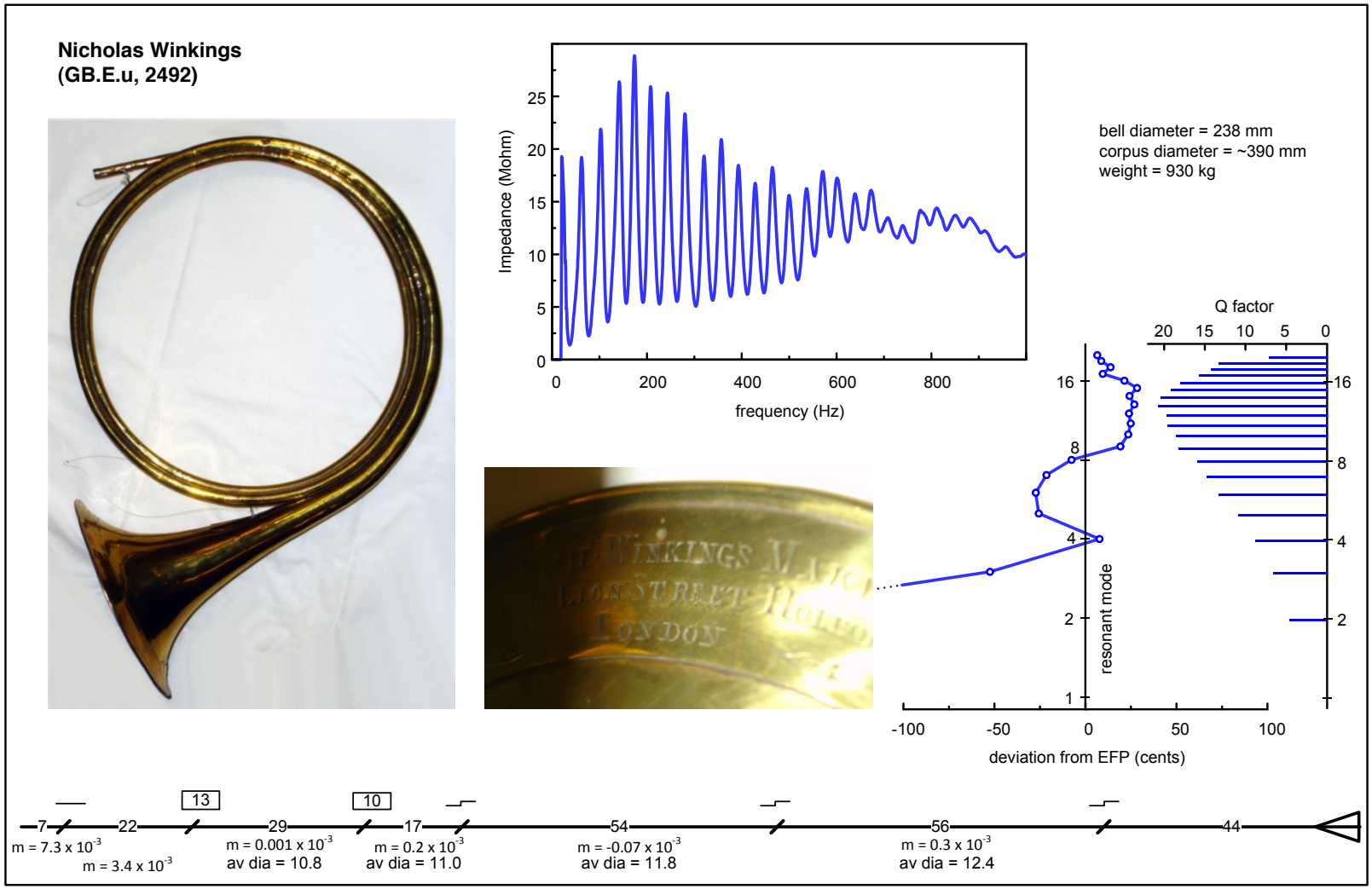


Figure 7.2: Data sheet showing acoustic measurements and design details on a horn by Winkings (GB.E.u, 2492).

7.4 Future research

The multi-dimensional approach to horn research described in this thesis is based on the idea of assigning values to, and measuring particular aspects of a large number of instruments. As such there is scope for greater systematisation in some areas of the current research and also for expanding the dataset. For example, some of the acoustic experimental techniques used in Chapters 3 and 4 for exploring tonal variation and lipping potential were limited to horns located in Edinburgh due to the impracticalities of transporting instruments from further afield to the experimental laboratories at the University of Edinburgh. This dataset could potentially be expanded however, by carrying out computational simulations with bore profile measurements as the input to the model, in order to predict the tonal characteristics and acoustic response of many more horns. It would also be interesting to create a ranking system based on a variable such as the brassiness potential parameter of an instrument in order to explore the chronology of changing tonal characteristics in a more structured way.

The ergonomic analysis carried out in Chapter 5 provided a novel and visual approach to looking at the issue of hand technique. This idea could now be carried further by creating a system in which an instrument is given a rating based on how easy it might be to play with the hand in the bell. A suitable method for assigning a 'comfort' rating might be to use predictive equations already developed in the field of biomechanics. This would allow an objective and chronological study of the ergonomic comfort of early horns.

As a tool for investigating early horn design, the bore profile comparison software described in Chapter 6 provides an ideal starting point. Interesting examples brought to light by the software can then be analysed from a number of different perspectives, demonstrating a new and integrated approach to early horn research. The analytical approaches involved in the study of these historic horns are highly interdisciplinary, drawing on and expanding techniques and information gleaned from acoustic, taxonomic, ergonomic and archival research, and as such offer a new, more global approach to instrument analysis.

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Appendix A: Horn reference list

A.1 Maker

Table A.1 is a reference list of all horns included in this study, sorted alphabetically by instrument maker. In the case of a small number of horns, the instrument has undergone a major alteration since it was first made, e.g. the addition of valves or a new bell. In these cases, both makers have been listed where known. Alternative spellings of instrument maker names have been included in square brackets.

A.2 Collection

The name of the museum or collection to which each instrument belongs is listed here in a shortened format, but full details of the collection names can be found in the list of abbreviations at the beginning of this thesis. Twelve of the horns listed were not examined in person, but sufficient information was available from museum catalogues for the instruments to be included in ergonomic analysis. Footnote references indicate where this is the case.

A.3 AN

The accession numbers given by the respective collections appear under the heading 'AN', and in the few collections where no identifying system is in

place, a number has been assigned by the author (D.EU.s, NL.DH.schepel and GB.CAS.prowse).

A.4 Region

Where the place of origin of a horn is known, this is listed under the heading 'Region', and where there is some uncertainty, for example surrounding the many anonymous instruments, a suggestion has been made.

A.5 Date

In cases where a date of manufacture has been inscribed on the bell of an instrument, this is included in the table, but for all other horns, an approximate date of manufacture has been estimated. This is either based on information about the period during which an instrument maker was active at a particular address, (indicated in the table by the abbreviation '*fl*') or based on observation of details of manufacture. Information about instrument makers has mainly been extracted from *The New Langwill Index* [Waterhouse, 1993].

A.6 Reference

Where a specific instrument has been discussed in the main body of the thesis, references to the relevant sections have been provided. The majority of analysis described in this thesis was carried out by examining photographs and detailed bore profile measurements. This information was gathered on over one hundred of the horns listed here. It was also possible to take acoustic measurements of many of these horns, but it was only practical to carry out brassiness experiments on the horns in Edinburgh (GB.E.u and GB.E.chick).

Table A.1: A list of all the horns included in this study, including basic information and where relevant, references to which chapters the instruments were discussed in.

Maker	Collection	AN	Region	Date	Reference
Anger	CZ.Pnm	E 743	Kraslice	1780	
Angoulvant [?Amboulevart]	NL.DH.schepel	1	Paris	*fl* 1777-1791	
anonymous	A.KR.sk	Söl.011	?France	?19th c.	
anonymous	A.KR.sk	Söl.000	?France	?19th c.	
anonymous	A.W.km	720	?Dresden	early 18th c.	6.3.1
anonymous	A.W.km	721	?Dresden	early 18th c.	6.3.1, 6.3.3
anonymous	D.EU.s	1	?Bohemia	late 17th/early 18th c.	
anonymous	D.EU.s	2	?France	early 18th c.	
anonymous	D.LE.u*	1681	?Vogtland	*c*1820/25	
anonymous	D.LÜ.mk	1893/56	?Dresden	early 18th c.	6.3.1
anonymous	D.LÜ.mk	1893/57	?Dresden	early 18th c.	6.3.1
anonymous	D.LÜ.mk	1934/402	?Germany	late 18th/early 19th c.	
anonymous	D.LÜ.mk	4422	?Germany	late 18th/early 19th c.	6.3.3
anonymous	D.M.dm	4684	?Germany	?18th c.	
anonymous	E.B.mi	1487	?France	early 19th c.	
anonymous	E.B.mi	1488	?France	early 19th c.	
anonymous	F.P.cm	E.980.2.266	?France	late 18th c.	

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*Details taken from the catalogue of the Musikinstrumenten-Museum der Universität Leipzig [Heyde, 1982, Plate 60].

Maker	Collection	AN	Region	Date	Reference
anonymous	GB.E.u	2887	?England	late 18th/early 19th c.	3.4.2 4.3.4 5.2.2 6.3.1, 6.3.2
anonymous	GB.E.u	2888	?England	late 18th/early 19th c.	5.2.2
anonymous	GB.L.hm	296	?England	?18th c.	
anonymous	GB.NW.cm	1922.135.SH	?England	?18th c.	
anonymous	US.B.mfa	17.2001	?England	late 18th c.	6.3.3
Barth	A.KR.sk	Piz.003	Munich	*fl* 1833-1872	4.1.3, 4.3.4
Bauer	A.KR.sk	Söl.999	Prague	*fl c*1811-1835	
Benith	D.B.im*	3017	London	1738	
Bennet	GB.O.ub	603	London	early 18th c.	5.2
Besson	GB.E.chick	2006.1	Paris	*fl* 1864-1869	
Buchschwinder	CH.B.hm	1980.2123.	Ellwangen	1742	4.3.4
Canepel	US.W.si	95.269	Brussels	1729	
Carlin	B.B.mim	468	Paris	*fl a*1751-1780/81	
Carlin	F.P.cm	E.769	Paris	*fl a*1751-1780/81	
Carlin	F.P.cm	E.980.2.501	Paris	*fl a*1751-1780/81	
Carlin	GB.O.ub	64	Paris	*fl a*1751-1780/81	
Coll	E.B.mi	787	Igualada	early 19th c.	
Conn	GB.E.chick	2007.3	Abilene	2000	3.5, 3.4.3

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*Details taken from the catalogue of the Musikinstrumenten-Museum, Berlin [Krickeberg & Rauch, 1976, p. 107].

Maker	Collection	AN	Region	Date	Reference
Courtois	A.KR.sk	Piz.000	Paris	late 18th/early 19th c.	
Courtois	F.P.cm	E.1980.2.274	Paris	*fl* 1789-?1803	
Courtois	F.P.cm	E.980.2.276	Paris	*fl* 1816-1837	
Courtois	GB.E.u	4668	Paris	*c*1840	3.4.2
Cretien	F.P.cm	E.890	Paris	17th c.	
Delcourt	US.NY.mma	89.4.2419	Ath	late 18th/early 19th c.	
Droscheln	A.G.lj	14.921	Nuremberg	1647	
Egger	CH.B.hm	1980.2102.	Radolfzell	1720	
Ehe	CH.B.hm	1880.71.	Nuremberg	late 17th/early 18th c.	5.3 6.3.2
Ehe	CH.B.hm	1956.617.	Nuremberg	late 17th/early 18th c.	5.2, 5.3, 5.4.4
Ehe	D.N.gnm	MIR 72	Nuremberg	*c*1720	
Ehe	D.N.gnm	MIR 74	Nuremberg	*c*1720	
Ehe	F.P.cm	E.2354	Nuremberg	*fl* 1722-1771	
Ehe	US.B.mfa	17.1999	Nuremberg	*fl* 1692-1743	
Eichentopf	CH.B.hm	1980.2134.	Leipzig	1735	4.3.4, 6.3.4
Eichentopf	CZ.P.nm	E 85	Leipzig	1735	6.3.4
Eichentopf	CZ.P.nm	E 86	Leipzig	1735	
Eschenbach	CH.B.hm	1980.2091.	Neukirchen	1789	
Eschenbach	D.M.sm	73-35	Neukirchen	1795	
Eschenbach	F.P.cm	E.1675	Berlin	late 18th c.	
España	E.B.mi	784	Barcelona	early 19th c.	

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Maker	Collection	AN	Region	Date	Reference
Flemming	D.LE.u*	1678	Wrocław	*c*1800	
Franck	D.N.gnm	W 3013	Hildburghausen	1716	5.2, 5.4.5
Fratisch	CZ.Pnm	E 83	Prague	1752	
Fratisch	CZ.Pnm	E 84	Prague	1752	
Glier	CH.B.hm	1980.2039.	Neukirchen	1792	6.3.3
Graf	CH.B.hm	1980.2182.	Breitenbach	1745	
Grinwalt	US.W.si	65.603	Munich	1725	
Grünwoldt [?Grinwolt]	D.EU.s	3	Munich	1729	
Haas	CH.B.hm	1880.72.	Nuremberg	1682	
Haas	CH.B.hm	1980.2118.	Nuremberg	early/mid 18th c.	
Haas	D.N.gnm	MI 178	Nuremberg	*c*1770	
Haas	D.N.gnm	MI 179	Nuremberg	1724	
Haas	D.N.gnm	MIR 75	Nuremberg	*c*1745	
Haas	F.Pcm	E.1454	Nuremberg	early 18th c.	
Haas	GB.O.ub	605	Nuremberg	18th c.	
Hainlein	D.N.gnm	MI 361	Nuremberg	*c*1710	
Haltenhof	F.Pcm	E.1020	Hanau	1776	
Hofmaster	GB.E.u	3296	London	*c*1760	6.3.1, 6.3.2

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*Details taken from the catalogue of the Musikinstrumenten-Museum der Universität Leipzig [Heyde, 1982, Plate 58].

Maker	Collection	AN	Region	Date	Reference
Hofmaster	GB.E.u	3297	London	*c*1760	3.4.3 4.2.3, 4.2.4, 4.3.2, 4.3.3 5.2.2 6.3.1, 6.3.2
Hofmaster	GB.O.ub	606	London	*fl c*1751-1764	5.2.2
Hofmaster	GB.O.ub	607	London	*fl c*1751-1764	5.2.2
Huschauer/anonymous*	CZ.Pnm	E 413	Vienna	?1793/19th c.	
Jiráček	GB.E.chick	2003.1	Šaratice	2003	3.4.1
Kerner	A.G.lj	5.744	Vienna	1781	
Kerner	CZ.Pnm	E 608	Vienna	1794	
Kerner	CZ.Pnm	E 963	Vienna	1777	6.3.1
Kerner	CZ.Pnm	E 965	Vienna	1769	6.3.1
Key	GB.O.ub	62	London	*fl a*1805-1858	6.3.2
Koch	D.LE.u†	1661	Dresden	1689	
Koch	D.LE.u‡	1663	Dresden	1710	
Kodisch	D.N.gnm	MIR 76	Nuremberg	*c*1735	
Korn	D.LE.u§	3473	Mainz	*c*1825/30	

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*The garland on this instrument is inscribed with the name 'Joseph Huschauer' and appears to be originally dated '1793', but altered later to look like '1723'. Valves have also been added at a later date.
†Details taken from the catalogue of the Musikinstrumenten-Museum der Universität Leipzig [Heyde, 1982, Plate 12].
‡Details taken from the catalogue of the Musikinstrumenten-Museum der Universität Leipzig [Heyde, 1982, Plate 13].
§Details taken from the catalogue of the Musikinstrumenten-Museum der Universität Leipzig [Heyde, 1982, Plate 62].

Maker	Collection	AN	Region	Date	Reference
Körner	D.LE.u*	1686	Vienna	*c*1790	
Krause	D.LE.u†	1676	Berlin	*c*1800	
Krause/anonymous‡	CZ.Pnm	E 2257	Berlin	?1797/19th c.	
Kretzschmann	GB.E.u	531	Strasbourg	*c*1830	3.4.1, 3.4.2 4.3.2, 4.3.3
Lausmann	A.KR.sk	Piz.006	Linz	*fl a*1855-1879/80	4.3.3, 4.3.4
Lausmann	D.LE.u§	1672	Kraslice	1791	
Leichamschneider	CH.B.hm	1878.22.	Vienna	1718	4.3.3
Leichamschneider	CH.B.hm	1980.2013.	Vienna	1718	
Liebel	CZ.Pnm	E 408	Neukirchen	1777	
Liebel	D.LE.u¶	1674	Markneukirchen	1791	
Meinl & Lauber / Paxman	GB.E.chick	2008.1	Geretsried/London	mid/late 20th c.	3.4.1 4.2.2
Meinl	GB.E.chick	2004.2	Geretsried	2004	3.4.1 4.3.4
Nagel	A.KR.sk	Piz.002	Nuremberg	1663	

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*Details taken from the catalogue of the Musikinstrumenten-Museum der Universität Leipzig [Heyde, 1982, Plate 60].
†Details taken from the catalogue of the Musikinstrumenten-Museum der Universität Leipzig [Heyde, 1982, Plate 59].
‡The garland on this instrument is inscribed with the name 'August Friedrick Krause' but valves have been added at a later date.
§Details taken from the catalogue of the Musikinstrumenten-Museum der Universität Leipzig [Heyde, 1982, Plate 58].
¶Details taken from the catalogue of the Musikinstrumenten-Museum der Universität Leipzig [Heyde, 1982, Plate 58].

Maker	Collection	AN	Region	Date	Reference
Paxman	GB.E.chick	2001.1	London	2001	4.3.4 5.3.2 6.3.1
Pieltz	CZ.Pnm	E 406	Johannesburg	*c*1780	
Raoux	CH.B.hm	1980.2166.	Paris	mid/late 18th c.	
Raoux	CH.B.hm	1980.2265.	Paris	late 18th/19th c.	5.2
Raoux	D.LE.u*	1662	Paris	*c*1780	
Raoux	F.Pcm	E.259	Paris	1798	
Raoux	F.Pcm	E.968.7.1	Paris	*fl a*1695-*p*1734	
Raoux	F.Pcm	E.1676	Paris	late 18th c.	
Raoux	NL.DH.schepel	2	Paris	*fl* 1821-*p*1931	
Raoux	US.B.mfa	17.2000	Paris	*c*1780	
Sandbach	GB.E.u	203	London	*fl* 1810-1830	4.2.3 6.3.2
Saurle	A.KR.sk	Piz.005	Munich	*fl* 1799-1872	4.3.3, 4.3.4
Saurle	US.W.si	65.602	Munich	*fl* 1799-1873	
Schmidt	US.NY.mma	14.25.1623	Nuremberg	*fl* 1669-1720	
Schmidt	US.NY.mma	89.4.1117	Nuremberg	*fl* 1669-1721	
Schmied	CZ.Pnm	E 909	Pfaffendorf	1771	
Schmied	US.W.si	65.635	Pfaffendorf	1788	
Schwabe	D.LÜ.mk	1893/55	Leipzig	1767	

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*Details taken from the catalogue of the Musikinstrumenten-Museum der Universität Leipzig [Heyde, 1982, Plate 14].

Maker	Collection	AN	Region	Date	Reference
Seraphinoff	GB.E.chick	2007.2	Bloomington	2007	4.3.4
Shaw	A.KR.sk	216	London	*fl c*1783-1802	4.1.3, 4.3.3, 4.3.4 6.3.2, 6.3.3
Smith & Sons	GB.O.ub	63	Wolverhampton	early 19th c.	5.2 6.3.2
Stärtzer/Lausmann*	GB.L.hm	295	Vienna/Kraslice	late 18th c.	
Uhlmann	GB.CAS.prowse	1	Vienna	*fl* 1834-1904	3.4.2
Vermigli	US.W.si	95.319	Siena	?early 19th c.	
Werner	A.KR.sk	Piz.001	Dresden	*fl a*1728-*p*1772	4.3.4
Werner	CH.B.hm	1980.2098.	Dresden	1735	4.3.4 5.4.4
Werner	CH.B.hm	1980.2099.	Dresden	1735	
Werner	D.LE.u†	1664	Dresden	1740	
Werner	D.M.sm	85-24	Dresden	1772	
Winkings	GB.E.u	2492	London	*c*1760	5.2.2 6.3.2
Winkings	GB.E.u	2493	London	*c*1740	4.3.2, 4.3.3 5.2.2 6.3.1, 6.3.1, 6.3.2
Winkings	GB.E.u	2627	London	*c*1740	

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*The garland on this instrument is inscribed with the name 'Stärtzer' but it is possible that it ws added at a later date.
†Details taken from the catalogue of the Musikinstrumenten-Museum der Universität Leipzig [Heyde, 1982, Plate 54].

Maker	Collection	AN	Region	Date	Reference
Winkings	GB.NW.cm	1940.147	London	*c*1740-1760	6.3.1
Winkings	GB.O.ub	604	London	*fl* 1751-*p*1768	5.2.2 6.3.1

Appendix B: Bore profile data

B.1 Contents of enclosed CD

The enclosed CD includes files which were compared by the bore profile matching tool described in Chapter 6. For ease of reference, each file name consists of the name of the instrument maker, followed by the accession number of the horn in question. Included in the content of each text file is information about the collection, the date on which the measurements were taken, the accession number, and the name of the instrument maker. Further information about these instruments can be found in Appendix A. The bore profile measurements are presented in two columns: the first corresponds to axial length as measured from the entrance to the instrument; the second corresponds to internal bore diameter.

Appendix C: Additional lipping data

C.1 Mouthpiece results

Tables C.1 and C.2 list data from the lipping experiments discussed in Section 4.2.2, comparing different mouthpiece designs. The extent to which players were able to manipulate the pitch of a resonance both upwards and downwards is shown here as an average taken from all relevant sound recordings. In the bottom section of both tables, the range refers to the average total pitch change across each resonance. Highlighted in light grey is the mouthpiece on which each player was able to achieve the greatest extent of pitch manipulation.

C.2 Horn results

Tables C.3, C.4 and C.5 list data from the lipping experiments discussed in Section 4.2.3, comparing different early horns. The extent to which five different horns responded to pitch manipulation on three different resonances is shown here in these three tables. Average upward and downward pitch bends are listed along with the average total pitch change across each resonance. Also included is the maximum recorded pitch bend for each horn and the Q value of the resonance in question, taken from acoustic input impedance measurements. Horns are ranked according to average pitch range.

Table C.1: Lipping results from 5 players manipulating the pitch of the 4th resonance on three different mouthpieces. Grey shadings indicate the mouthpiece on which each player achieved maximum flexibility of pitch.

4th resonance		Average (cents)				
Lipping	Mouthpiece	Player 1	Player 2	Player 3	Player 4	Player 5
Upwards	Shallow (20)	55	53	72	76	54
	Medium (23A)	70	75	48	47	38
	Deep (35)	65	90	72	81	61
Downwards	Shallow (20)	-199	-228	-149	-221	-170
	Medium (23A)	-180	-233	-187	-200	-170
	Deep (35)	-182	-209	-194	-204	-176
Range	Shallow (20)	254	281	221	297	224
	Medium (23A)	250	308	235	247	208
	Deep (35)	247	299	266	285	237

Table C.2: Lipping results from 5 players manipulating the pitch of the 11th resonance on three different mouthpieces. Grey shadings indicate the mouthpiece on which each player achieved maximum flexibility of pitch.

11th resonance		Average (cents)				
Lipping	Mouthpiece	Player 1	Player 2	Player 3	Player 4	Player 5
Upwards	Shallow (20)	35	36	36	34	36
	Medium (23A)	25	45	35	37	30
	Deep (35)	33	37	36	35	32
Downwards	Shallow (20)	-25	-36	-28	-34	-24
	Medium (23A)	-34	-35	-26	-43	-22
	Deep (35)	-28	-39	-28	-29	-27
Range	Shallow (20)	60	72	64	68	60
	Medium (23A)	60	80	61	80	52
	Deep (35)	61	76	64	64	59

Table C.3: Lipping results showing how 5 different early horns respond to player pitch manipulation on the 4th resonance. The Q value of the 4th resonance on each horn is also listed.

4th resonance	Average (cents)			Maximum (cents)	Q value
Maker	Upwards	Downwards	Range	Range	
Sandbach (203)	53	-168	221	234	12.0
Hofmaster (3296)	66	-193	259	269	11.4
anononymous (2888)	120	-179	299	311	10.2
Kretzschmann (531)	95	-204	299	313	12.2
Winkings (2492)	114	-203	317	350	8.5

Table C.4: Lipping results showing how 5 different early horns respond to player pitch manipulation on the 10th resonance. The Q value of the 10th resonance on each horn is also listed.

10th resonance	Average (cents)			Maximum (cents)	Q value
Maker	Upwards	Downwards	Range	Range	
Sandbach (203)	49	-24	73	81	21.1
anononymous (2888)	45	-31	76	91	17.4
Hofmaster (3296)	46	-40	86	91	20.4
Kretzschmann (531)	58	-29	87	97	21.5
Winkings (2492)	59	-35	94	106	18.4

Table C.5: Lipping results showing how 5 different early horns respond to player pitch manipulation on the 11th resonance. The Q value of the 11th resonance on each horn is also listed.

11th resonance	Average (cents)			Maximum (cents)	Q value
Maker	Upwards	Downwards	Range	Range	
Sandbach (203)	39	-17	56	62	22.3
Winkings (2492)	41	-23	64	70	19.4
anononymous (2888)	39	-28	67	72	18.9
Kretzschmann (531)	47	-25	72	83	23.4
Hofmaster (3296)	45	-37	82	90	22.5

Appendix D: Photographic distortion

D.1 Deviation in measurements

In Chapter 5, ergonomic horn data was gathered by calculating and recording measurements taken from photographs of the instruments. The space and facility for taking photographs in the many different museums and collections visited varied, resulting in shots being taken from slightly different angles, distances, and levels of zoom. In order to explore the extent to which a distorted digital horn image could affect the calculations and measurements, a basic check was carried out. This involved analysing the dimensions on several images of a test horn, photographed from various positions. The resulting images are shown in Figures D.1-D.6.

As far as possible, in Figures D.1-D.5, the camera lens was positioned parallel to the plane of, and in line with the centre of the corpus of the instrument. The zoom facility was used only on the photograph in Figure D.4. Similar studies have been carried out in the field of forensics concerning potential distortion of photographic evidence [Rajshekar *et al.*, 2012; Rawson *et al.*, 1986].

The horn images were then scaled based on the width of the bell, so that corpus diameter, circularity and angle of the mouthpipe to the bell could be compared. The measurements from four of the photographed horns are shown in Figures D.7-D.10; the angle between the axis of the mouthpipe and that of the bell is shown in red, the corpus diameter in green, and a reference circle in blue has also been

Figure D.1: Photographed at 1 m distance from horn.

Figure D.2: Photographed at 0.5 m distance from horn.

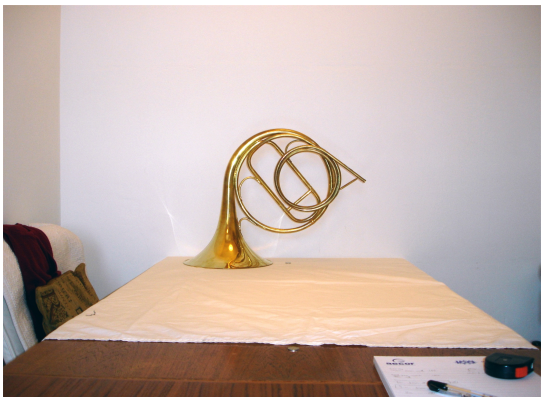

Figure D.3: Photographed at 2 m distance from horn.

Figure D.4: Photographed at 4 m distance from horn on maximum zoom.

Figure D.5: Photographed at 4 m distance from horn.

Figure D.6: Photograph at a 30° angle to the right of the horn at 2 m distance.

included in order to observe distortion more easily. The results from all images are included in Table D.1.

Table D.1: Deviation in measurements taken from images of a horn photographed from various positions.

Position of camera	Angle		Corpus diameter	
	Measured	Deviation (%)	Measured (mm)	Deviation (%)
1 m from horn	53.5°	0.9	310	1.0
2 m from horn	53.3°	0.6	314	0.3
4 m from horn	53.0°	0.0	315	0.6
zoom (4 m away)	53.9°	1.7	317	1.0
30° angle (2 m away)	51.5°	2.8	311	0.6
Average	53.0°	1.2	313	0.7

From these results it can be calculated that the average percent deviation is 1.2 % concerning the measured angle and 0.7 % concerning the measured corpus diameter, whilst the maximum percent deviation is still only 2.8 %. Unsurprisingly, the circularity of the corpus on the photograph of the horn taken at an angle differed most noticeably from that of the other horn images, but nevertheless the measurements show less deviation than might be expected.

Assuming that the method of taking measurements from a digital image is accurate, the degree of deviation in these results is small enough that it can be considered negligible. It should be noted that these photographs were taken at exaggerated distances and angles, but in practice the setup shown in Figure D.1 was possible for the large majority of instruments. The reproducibility of the measurements meant that good quality photographs in catalogues of collections could also be included in the dataset, helping to expand the range of the survey of horns.

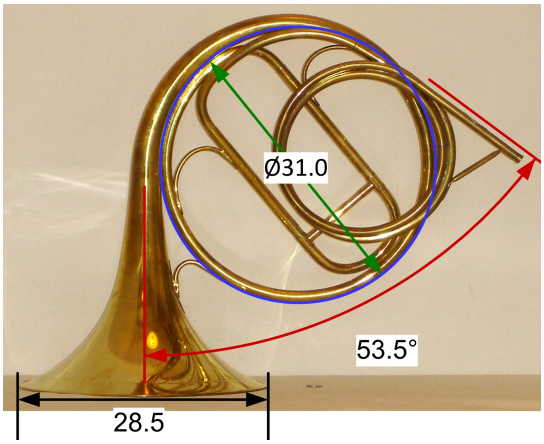

Figure D.7: Scaled dimensions from the image in Figure D.1 (1 m away).

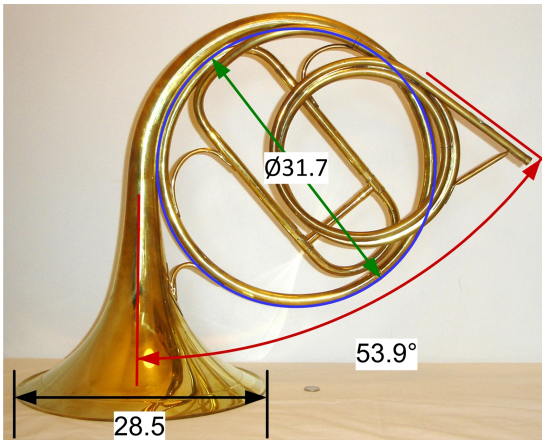

Figure D.8: Scaled dimensions from the image in Figure D.4 (with zoom).

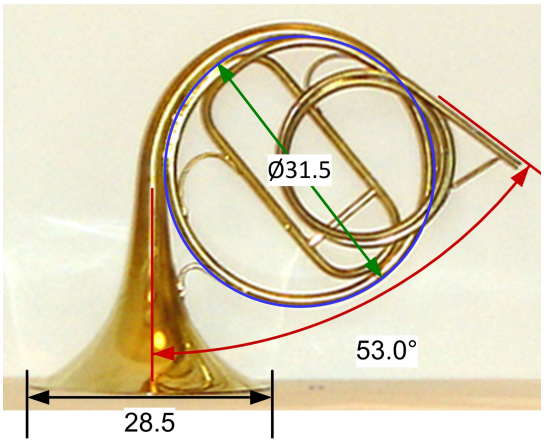

Figure D.9: Scaled dimensions from the image in Figure D.5 (4 m away).

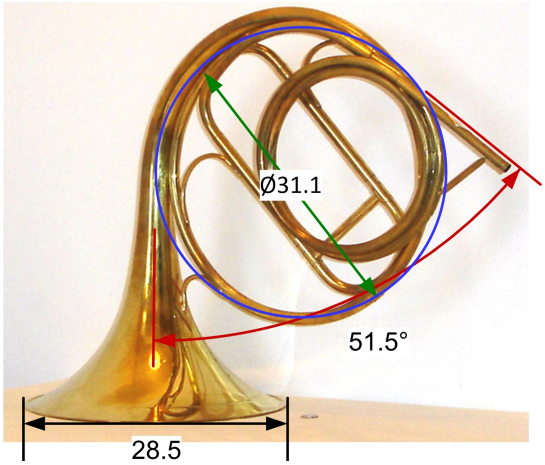

Figure D.10: Scaled dimensions from the image in Figure D.6 (at an angle).

Appendix E: Related published articles

The two articles included here use similar analysis techniques to those described in this thesis but are concerned with slightly different, but related subject matter. The first article discusses modern horn player technique and the possibilities for timbral manipulation and variation, whereas the second article makes an organological examination of the family of Wagner tubas and related instruments. Acoustic analysis was the main research tool employed in both investigations, and these examples help to highlight the interdisciplinary nature and potential of this approach to research.

E.1 Player technique

Title: Norman, L., Chick, J., Campbell, M. & Gilbert, J. (2010). Player control of 'brassiness' at intermediate dynamic levels in brass instruments. *Acta Acustica united with Acustica*, **96**, 614-621.

Abstract: see the summary at the beginning of the article.

E.2 Organology

Title: Norman, L., Myers, A. & Campbell, M. (2010). Wagner tubas and related instruments: An acoustical comparison. *Galpin Society Journal*, **LXIII**, 143-158.

Abstract: The Wagner tuba is often described as a cross between a horn and a tuba and its distinctive timbre has ensured its survival to the present day, but little is known about the acoustical characteristics of the instrument. Around the time when the Wagner tuba first became established, towards the end of the 19th century, it was not uncommon for a number of similar instruments such as baritones and cornophones to be used as substitutes when Wagner tubas proved difficult to obtain, and so examples of these related instruments have also been included for comparison in this study, along with Wagner tubas by makers Alexander, Mahillon, Moritz, and Schopper. The tests carried out involved the measurement of input impedance and of brassiness potential in order to explore variations in response, intonation, and timbre. These results are discussed with reference to detailed physical measurements of the bore profiles of the instruments, the dominant factor found to influence instrument character and acoustics.

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Player Control of *'Brassiness'* at Intermediate Dynamic Levels in Brass Instruments

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Summary

An increase in the dynamic level of a brass instrument from *forte* to *fortissimo* generally brings about a change in timbre to a much brighter sound, often described as 'brassy'. This phenomenon is due to non-linear wave propagation along the bore of the instrument, which generates significant spectral enrichment in the higher harmonics. The dynamic level at which this change occurs is not always clearly defined and some brass players have found that, by employing slight changes in embouchure, they have a degree of control over the level of brassiness at a constant dynamic. Experimental data from playing tests are presented, showing that players employing this technique are able to modify the gradient of the input pressure wave front as it is formed in the mouthpiece. Numerical simulations based on weakly non-linear shock theory, with experimental data from brassy and non-brassy mouthpiece measurements as the input boundary conditions, confirm the assumption that the increase in spectral enrichment is primarily a consequence of enhancement of non-linear wave steepening resulting from a change in shape of the waveform in the mouthpiece.

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1. Introduction

One of the most striking characteristics of brass instruments is their wide dynamic range and the change in timbre that occurs from quiet to loud playing. At the loudest dynamic levels the tone of the instrument becomes typically brassy or *cuivré*. This is as a direct result of non-linear propagation of the pressure wave as it travels along the cylindrical sections of the bore of the instrument [1], causing the higher frequency components of the sound to be strongly excited and thus generating a bright and brilliant timbre. This style of playing is achieved most easily at the highest dynamic levels where non-linear propagation dominates. However, non-linear propagation of the wave front is not confined to the extremes of loud playing. It has also been observed to some extent at intermediate dynamic levels. Interestingly, brass players often talk about playing with or without a brassy 'edge' to the sound, but in reality the transition between a non-brassy and brassy timbre is not well defined [2].

The dominant factor influencing the timbre of the note is the bore profile [3]. However, mouthpiece dimensions [4], and construction material of the instrument [5, 6] have also been cited as affecting the timbre. The issue of player control of brassiness through embouchure manipulation, the focus of this paper, is an area which has received little attention. Whereas the physical changes to the instrument can be measured in a relatively objective manner, the very nature and complexity of a player's lips and vocal tract make systematic measurement and analysis of variation in playing technique more difficult.

It is interesting to observe that player control of brassiness is much more easily achieved in brass instruments than in woodwind instruments. This is because brass instruments are generally more receptive to embouchure control than those in the woodwind family since properties of the reed (predominantly its stiffness) in an instrument such as the clarinet or oboe, are more or less fixed, whereas the brass player has a greater degree of control over the lips by changing the tension in the lip muscles, and the pressure and angle of the mouthpiece [7].

In section 2 of this paper we present a summary of the underlying physical principles which determine the onset of non-linear propagation in brass instruments, and point to some of the possibilities that may be available to the player to control the spectral content of the sound. Section 3 documents an experimental procedure for assessing player control of the onset of brassiness in a french horn, and examines the results from playing tests. A numerical model of the instrument used for these experiments is de-

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scribed in section 4, and the output from this is used to show the separate contributions of linear and non-linear propagation to the spectral content of the radiated sound.

2. Brightness and brassiness: theoretical background

2.1. Factors affecting spectral enrichment

An elementary physical model capable of explaining the generation of sound by a brass instrument is illustrated in Figure 1. The lips of the player are represented as a valve modulating the flow of air from the player's lungs into the instrument. For a suitable choice of parameters the system behaves as a positive feedback loop, generating a self-sustaining oscillation [8]. The volume flow rate q_{in} through the valve is related to the acoustic pressure p_{in} in the mouthpiece of the instrument by a non-linear equation of the form

$$q_{in}(t) = S(t)\sqrt{\frac{2\big(P_M - p_{in}(t)\big)}{\rho}}, \tag{1}$$

where $S(t)$ is the area of the opening between the lips, P_M is the pressure in the player's mouth, and ρ is the density of air. The non-linear nature of equation (1) has the important consequence that even if the players lips were to open and close sinusoidally, the air flow into the mouthpiece would have a non-sinusoidal waveform. The generation of upper harmonics is an inherent feature of the flow control valve, and the richness of the harmonic spectrum in the mouthpiece waveform increases with the pressure amplitude.

In fact, $S(t)$ does not normally have a strictly sinusoidal waveform. Studies of lip motion in brass players using transparent mouthpieces have also shown that the relationship between the opening height of the lips and the open area is typically non-linear, and it has been demonstrated that this non-linearity can contribute significantly to the spectral enrichment of the resulting sound [9].

A further factor which makes a significant contribution to the brightness of timbre in brass instruments is the high-pass filter effect of radiation from the bell of the instrument. A harmonic component at a low frequency ω can be considered as being radiated by a monopole source whose strength Q_{out} is proportional to the pressure amplitude of the standing wave at frequency ω in the resonator. The resulting radiation far field is described by

$$p_{rad} = \frac{\mathrm{j}\omega Q_{out}\rho_0}{4\pi r}\exp \mathrm{j}\big(\omega t - kr\big), \tag{2}$$

where k is the wave number, and it is assumed that $1/k$ is much larger than the bell radius. The dependence of the amplitude on ω implies a 6 dB/octave treble boost in the transfer function from internal to radiated pressure. Above the bell cutoff frequency, which is typically around 1.5 kHz for a trumpet, the transfer function is close to unity and independent of frequency [10].

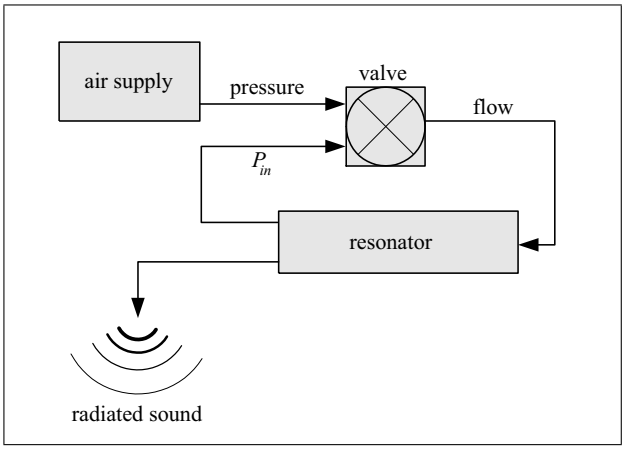

Figure 1. Feedback loop model of a brass wind instrument.

The model described so far includes a localised non-linear element in the flow control valve, but assumes that the behaviour of the sound waves in the resonating air column and in the radiation field can be described using linear acoustics. However, this model is incapable of explaining the dramatic increase in the relative amplitudes of the upper harmonics which occurs in very loud playing. This is due to non-linear propagation of the sound waves travelling from the mouthpiece to the bell. For *fortissimo* playing the pressure amplitude in the mouthpiece of a brass instrument can be of the order of 10 kPa; the linear acoustic assumption of constant sound propagation velocity is then inadequate. For the weakly non-linear case, the propagation speed c is given by [11]

$$c = c_0 + \left(\frac{\gamma + 1}{2}\right) v, \tag{3}$$

where c_0 is the propagation speed in the linear approximation, γ is the ratio of specific heats and v is the acoustic particle velocity. The implication of equation (3) is that, for the part of the acoustic cycle in which v is positive, the speed of propagation increases with amplitude. This can lead to the higher parts of the wave catching up with the lower parts, steepening the rising wavefront, and eventually giving rise to a shock wave.

For a cylindrical pipe, the distance x_s which the wave travels before the shock wave is fully developed is given by the expression

$$x_s = \frac{2\gamma P_{at} c_0}{(\gamma + 1)\big(\mathrm{d}p_{in}/\mathrm{d}t\big)_{max}}, \tag{4}$$

where P_{at} is atmospheric pressure. The distance to shock formation thus depends inversely on the maximum value of the rate of change of the input pressure.

A brass instrument like a trombone has a substantial cylindrical section and then a section where the bore expands towards the bell. In the expanding section the rate of steepening of the travelling wave is diminished because the sound energy is distributed over an increasingly large cross-section, thereby reducing the acoustic velocity. This

effect can be taken into account by introducing the coordinate stretching function $z(L)$,

$$z(L) = \int_0^L \frac{D(0)}{D(y)}\,\mathrm{d}y, \tag{5}$$

where $D(0)$ is the diameter at the input, $D(y)$ is the diameter at a distance y along the axis of the tube, and L is the overall length of the instrument. $z(L)$ is the length of the cylindrical tube of diameter $D(0)$ which has the same degree of non-linear steepening as the instrument in question.

2.2. Player control of timbral enrichment

The question addressed in this paper is the extent to which a brass player can control the degree of spectral enrichment due to non-linear propagation, without significantly changing the amplitude of the sound. One option is to increase the length of the instrument tube: on a trombone, for example, the note F3 can be played with the slide in first position (fully retracted) or 6th position (almost fully extended). In the second case, the longer propagation length allows the non-linear steepening to develop further, and in addition the increased proportion of cylindrical tubing reduces the co-ordinate stretching function. The note can therefore be played with a more brassy timbre in sixth position than in first position at a given dynamic level.

Some players claim to be able to exercise this type of timbral variation without altering the tube length. The widely respected horn player and teacher Philip Farkas, for example, suggests that a brassy tone can be achieved by adopting a more 'smiling' embouchure rather than a 'whistling' one for less brassy playing [12]. Inspection of equation (4) shows that timbral change such as this could be achieved if the player were able to modify the mouthpiece waveform so as to increase the steepness of the rising edge, without altering its amplitude. The experiments and simulations described in the following sections were designed to test the hypothesis that this is indeed the mechanism used by players.

It is important to recognise that a modification of the mouthpiece waveform could well have a direct effect on the timbre of the radiated sound without taking non-linear propagation into effect. If the rising edge of the pressure waveform is steepened, it is likely that the mouthpiece spectrum will have an increased proportion of upper harmonics; the linear pressure transfer function will accentuate this effect through the treble boost implied by equation (2). It was therefore necessary to design the experiments and simulations to be able to separate the linear and non-linear contributions to the spectral enrichment.

It is worth noting however that the non-linear steepening depends on the form of the time domain signal in the mouthpiece rather than the mouthpiece frequency spectrum. The two pressure waveforms illustrated in Figure 2 have the same frequency spectra, but the upper wave would develop into a shock wave in a much shorter propagation distance than the lower wave.

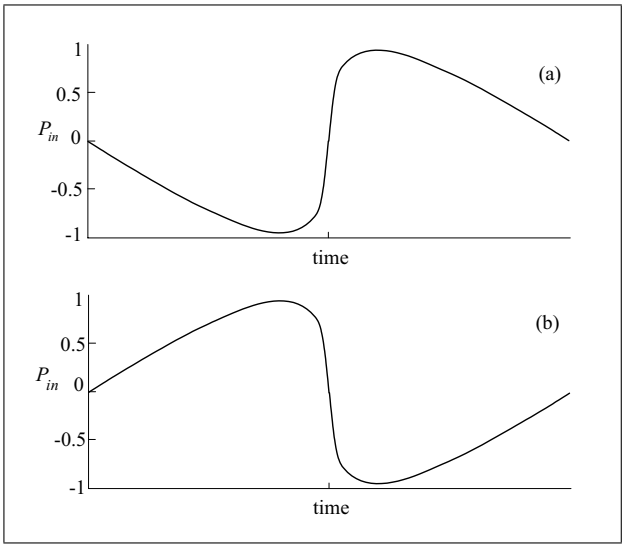

Figure 2. By changing the value of dP_{in}/dt the player has some control over non-linear propagation effects even when the spectral content of the input wave is unchanged: (a) a high value of dP_{in}/dt will induce large non-linear effects, (b) a low value of dP_{in}/dt will reduce non-linear effects.

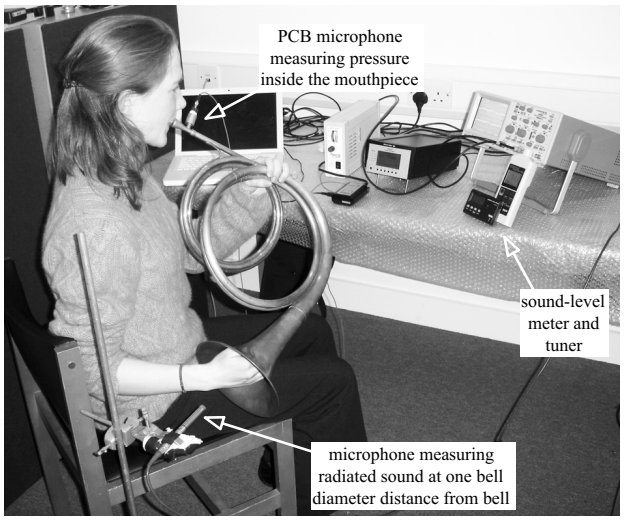

Figure 3. Experimental set up for embouchure control of brassiness playing, showing the positions of the microphones and sound-level meter.

3. Experimental procedure and results

The experimental set-up for examining the relationship between sound pressure in the mouthpiece and that of the radiated sound from the bell of the instrument is shown in Figure 3. The pressure in the mouthpiece of the instrument was measured using a 106B PCB Piezotronics dynamic pressure transducer. A commercially available horn mouthpiece, a Paxman-Halstead-Chidell (PHC 22), was modified to accommodate the PCB microphone into the backbore of the mouthpiece as shown in Figure 4. The radiated sound from the bell of the instrument was measured using a Bruël and Kjær 4192 pressure-field microphone, located one bell diameter from the plane of the bell of the

instrument. The signals from both transducers were sampled at 44.1 kHz.

A total of six professional and skilled amateur horn players were asked to provide playing samples. The instrument used for the tests was a Meinl & Lauber/Paxman 'baroque' horn modelled after an 18th-century instrument by Huschauer, Vienna c.1770. The instrument was crooked in D with a tube length corresponding to a nominal pitch of D_1 (approx. 4.4 m). The players were also invited to use their own instruments if they wished. However, the Meinl & Lauber/Paxman was judged to be most amenable to player control of brassiness, and the results presented are from this instrument.

The players were given a familiarisation period with the instrument before recording the test data. For the tests, the players could either sound pairs of notes, approximately 1–2 seconds each in duration, both at the same dynamic level, but one brassy and the other non-brassy; or the player could sound a single note (2 or more seconds in duration) at constant dynamic level, and change the timbre of the note as it was played. The pitch D_3 was chosen as the reference for the experiments. This is a mid-range note for the horn in D and was found to be a comfortable pitch for players to manipulate the timbre using only the embouchure. Tests were performed with the hand supporting the bell of the instrument as is usual practice and most comfortable for horn players, and also without the hand in the bell.

To assist the players with keeping the sound at constant pitch and dynamic level they were provided with a sound-level meter (set to A-weighting) and a digital tuner. The dynamic level at which the players found that the timbre could most easily be controlled was, in musical terms, *forte*, but not *fortissimo*. This varied marginally from player to player but was normally in the range 96–100 dB with the sound level meter positioned one metre in front of the player as shown in Figure 3. For the results presented here, players were able to maintain the sound pressure level to within ±1 dB of their chosen target. Some players also found it useful to watch the pressure signals, sampled in the mouthpiece and at the bell, on an oscilloscope whilst playing.

3.1. Results

Figure 5 shows examples of the frequency spectra of the radiated sound for brassy and non-brassy tones, played at the same dynamic level. The increase in strength of the higher frequency harmonics in the brassy tone compared with that of the non-brassy tone can clearly be seen. It should be noted that although the difference in timbre between the displayed brassy and non-brassy tones is significant and could easily be heard by the listener, these are by no means examples of the extremes of brassy and non-brassy playing. These extremes occur at the very quietest and loudest dynamic levels where embouchure manipulation plays a much less significant role than intensity level in determining spectral content.

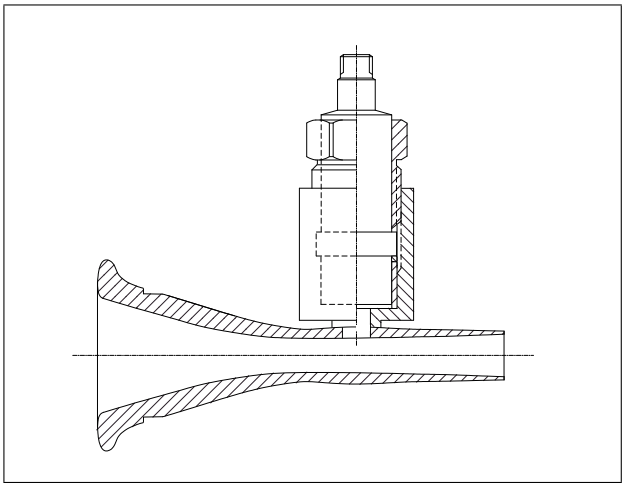

Figure 4. Horn mouthpiece and microphone assembly.

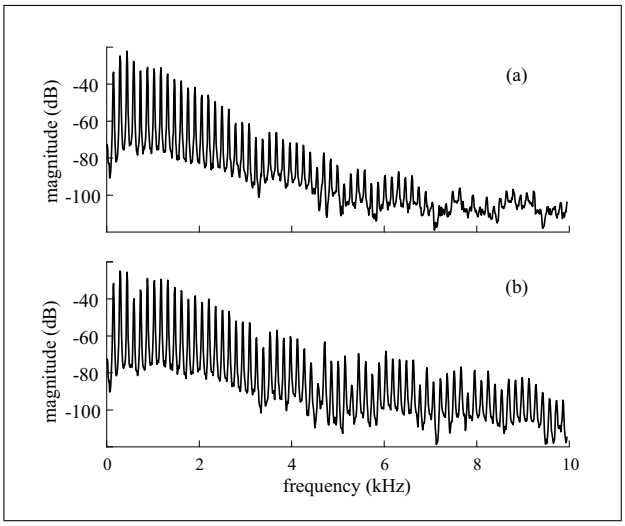

Figure 5. Frequency spectra of the radiated sound measured at one bell diameter from the bell exit for the note D_3, for a non-brassy tone (a), and a brassy tone (b). Both tests were played at nominally the same dynamic level.

Figure 6 shows the peak values of the frequency spectra for brassy and non-brassy pressures measured at the bell of the instrument and the corresponding pressure measured in the mouthpiece. Close inspection of this data shows that for frequencies above about 3.5 kHz the difference in spectral content of the mouthpiece pressure between brassy and non-brassy measurements is negligible. In contrast to this, the difference in spectral content of the radiated sound at higher frequencies is large, confirming that spectral enrichment is not simply occurring in the mouthpiece.

This difference is highlighted further in Figure 7 which shows the change in the magnitude of peak values between radiated non-brassy and brassy sound pressure levels; and the change in magnitude between the input (mouthpiece) pressures levels for non-brassy and brassy playing, ie the gain in going from non-brassy to brassy. Peak values are averaged over 1 kHz bins. This graph shows that even at approximately the same dynamic level, large differences in

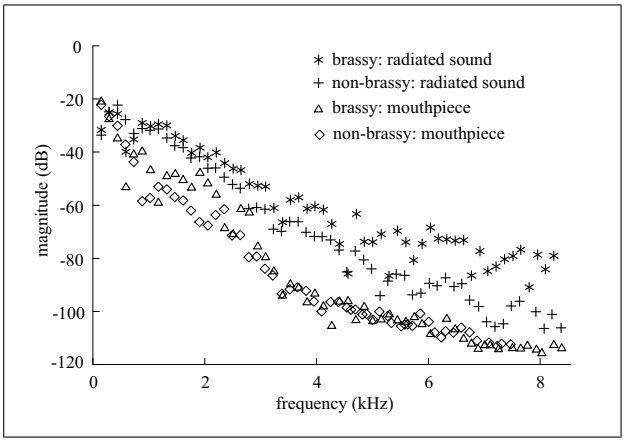

Figure 6. Spectral envelopes of brassy and non-brassy tones from mouthpiece and radiated sound. Notes D_3 played at constant dynamic level on a 4.4 m horn in D.

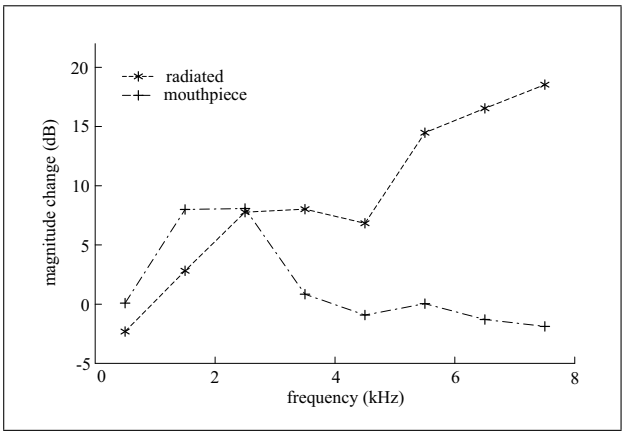

Figure 7. Change in the magnitude of peak values going from a non-brassy to a brassy sound for radiated and mouthpiece pressures. Notes D_3 played at constant dynamic level on a 4.4 m horn in D. Peak values are averaged over 1 kHz bins.

spectral content can clearly be seen where the two curves diverge. For example, in the range 6 to 7 kHz the pressure level in the mouthpiece decreased by 1 dB in the transition from non-brassy to brassy, but increased in the radiated sound by more than 16 dB. This would suggest that for a particular instrument, non-linearity is to some extent dependent not only on the intensity of the sound produced, but also on the way in which the player is able to control and alter the input waveform.

Figures 8 and 9 show the pressure waveforms recorded in the mouthpiece for a non-brassy and a brassy tone of pitch D_3. Although the pressures measured in the mouthpiece (Figures 8a and 9a) appear broadly similar, on close inspection it can be seen that the rising edge of the wave is steeper for the brassy tone than for the non-brassy tone. The rate of change of pressure in the mouthpiece, $\mathrm{d}P_{in}/\mathrm{d}t$, is also shown in both cases. For the mouthpiece signal which produces a non-brassy tone, the gradient of the wavefront is shown to be slightly more than 10 MPa/s, while that for the brassy tone displays a gradient of more than 15 MPa/s. Thus the 'brassy' mouthpiece wavefront is

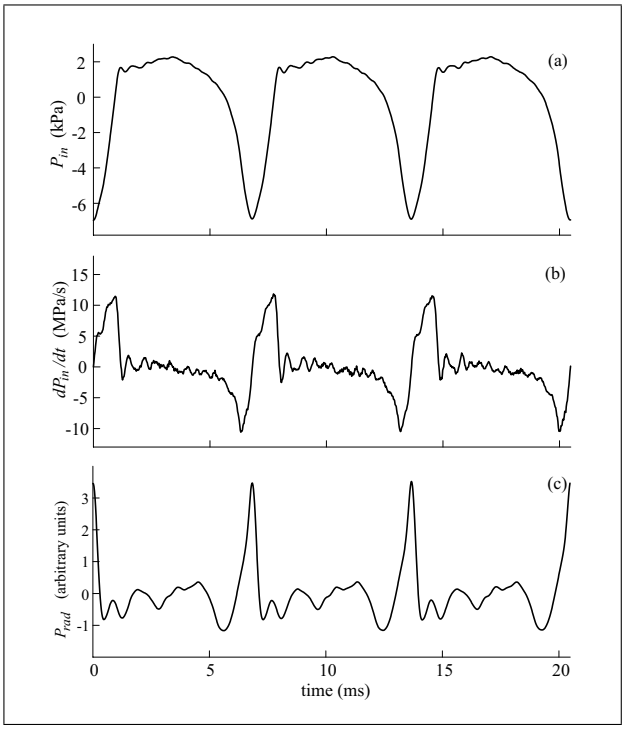

Figure 8. Measured data from non-brassy tests for the note D_3. (a) shows the mouthpiece pressure waveform; (b) shows the rate of change of mouthpiece pressure; (c) shows the radiated pressure waveform.

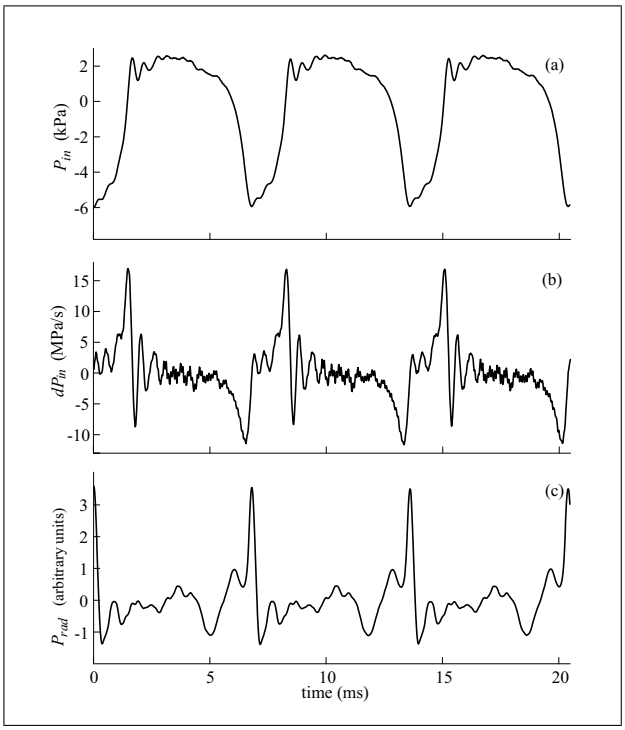

Figure 9. Measured data from brassy tests for the note D_3. (a) shows the mouthpiece pressure waveform; (b) shows the rate of change of mouthpiece pressure; (c) shows the radiated pressure waveform.

approximately 50% steeper than that of the 'non-brassy' signal.

4. Discussion and comparison with simulated results

The experimental results presented in section 3 show that when a player manipulates the tone of the horn by embouchure control in order to make the sound brassier, a steepening of the rising edge of the mouthpiece pressure waveform occurs. This change in shape of the waveform is not a result of a change in dynamic level or pitch, as these parameters have been kept constant. Reference to equation (4) shows that an increase of 50% in the value of $(dp_{in}/dt)_{max}$ will lead to a reduction by the same factor in the distance to shock formation x_s. Even if a shock wave does not fully develop in the length of the instrument, the rate of wave steepening, and therefore of spectral enrichment, will be substantially increased.

Wave steepening such as this occurs more readily in instruments which have a significantly long section of narrow cylindrical tubing, which is the reason that trumpets and trombones generally sound brassier than euphoniums and bugles [3]. The latter two instruments have a greater proportion of flaring or conical tubing and this causes any build up of pressure from the preceding cylindrical section to dissipate more rapidly as the diameter of the bore increases.

The findings from these experimental results can be assessed further by exploiting a numerical simulation tool which is able take into account the non-linear propagation phenomenon in non-uniform ducts such as brass instruments by solution of the generalised Burgers' equations [9]. Using this model, the relative contribution of the nonlinear propagation effects in the radiated sound can be estimated separately from the linear effects by carrying out simulations with and without the inclusion of the nonlinear term in the generalised Burgers' equations. It should be emphasised that this excerise is carried out purely to illustrate the significance of the nonlinear contribution, which is always present in high level propagation in the real world.

The frequency model simulation method is based on previous publications dedicated to uniform ducts and clarinet-like instruments [13, 14], and has been adapted here to apply to non-uniform ducts and brass instruments. The simulation can be summarized as follows: postulating the pressure spectrum P_{in} at the input end, a radiated impedance boundary condition at the output end (from Causse *et al.* [15]), and the bore geometry of the instrument, the pressure and velocity acoustic fields are first calculated everywhere inside the bore using the weakly nonlinear approximation. Indeed, the interaction between the simple waves propagating in each direction is supposed to be negligible, as in the linear approximation. The numerical solution to these equations, and details of the numerical harmonic balance convergence methods, are detailed in [13]. The volume velocity spectrum Q_{out} at the output end of the instrument is estimated by multiplying the output area by the output acoustic velocity spectrum. By using the low frequency approximation for a monopole having

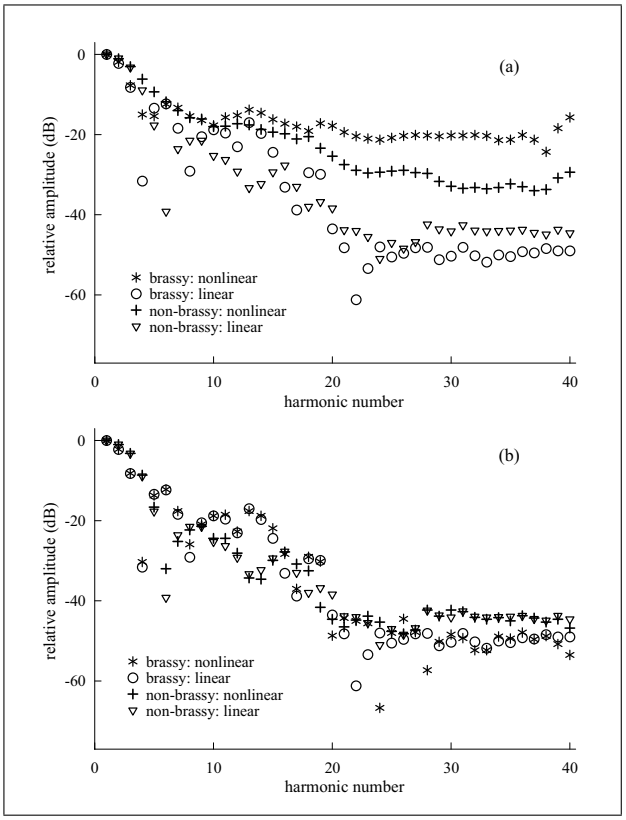

Figure 10. Spectral envelopes of brassy and non-brassy tones (amplitudes shown are relative to the fundamental, in dB): (a) modelled values of radiated sound with and without nonlinear propagation; (b) modelled values of radiated sound at *pianissimo* dynamic, where the *pianissimo* input is synthesized by decreasing the levels used in the previous simulation by 20 dB.

a volume strength equal to Q_{out}, a radiated pressure spectrum and its spectral centroid are estimated at a distance r from the open end of the pipe from equation (2).

Simulations were performed using the bore geometry for the Meinl & Lauber/Paxman horn described in section 3, tuned to a nominal pitch D_1 (horn length of approximately 4.4 m). Two pressure spectra, P_{in}, at the input end are used as input data for the simulations. These are taken directly from experimental data collected in the side of the mouthpiece backbore during playing tests, as described above: one corresponding to a waveform which produces a brassy tone, the other a waveform which produces a non-brassy tone. The original input data can be seen in Figure 6, and the results of the simulations can be seen in Figure 10.

For each input data set the model was run twice: first, taking into account the non-linear propagation effects; and second, without taking into account the non-linear effects, shown in Figure 10a. In the first case, the displayed results exhibit a clear offset in the high frequency part of the spectral envelopes between the brassy and non-brassy tones. This offset is qualitatively comparable to that of the measured data shown in Figure 6. This offset is clearly a consequence of the non-linear propagation and not simply due to the small differences in mouthpiece spectra. Indeed,

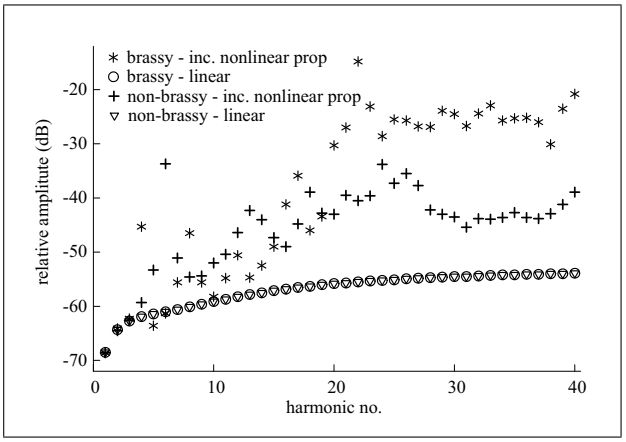

Figure 11. Transfer function, P_{rad}/P_{in}, corresponding to brassy and non-brassy tones from simulations with and without non-linear propagation.

if the non-linear propagation is not taken into account in the simulations, then the offset disappears and the calculated radiated spectral envelopes are more or less the same even at high frequencies as shown in Figure 10a.

The pressure transfer function between the radiated and the input pressures in the simulations are shown in Figure 11. It is known that differences in amplitude between the radiated spectral components and corresponding components in the mouthpiece are not constant over all dynamic levels due to increasing non-linearity as the sound intensity increases [16]. However, Figure 11 shows that even at constant dynamic levels, for different input waveforms (specifically having different dP_{in}/dt of the wave front), large differences in amplitude can clearly be seen where the two curves diverge. The 'linear limit' can also be seen in Figure 11 showing the typical high-pass filter effect of radiation.

A second simulation was performed (with and without taking into account the non-linear propagation effects) in order to simulate *pianissimo* playing; the results are shown in Figure 10b. The input data for this are synthesized from the same two measured mouthpiece pressure spectra, P_{in}, from the previous simulation, globally decreased by 20 dB. Figure 10b shows that at this quiet dynamic there is now little or no difference in the high frequency part of the spectral envelopes between the brassy and non-brassy tones. This is not surprising since we know that at *pianissimo* levels, non-linear propagation is not significant.

5. Conclusion

The six horn players studied demonstrated a wide range of ability to modify the timbre of a note while maintaining a constant dynamic level. The player whose results were discussed in section 3 was most consistently able to add or subtract a brassy edge to the sound of a mid-range note played at a constant *forte* dynamic level. Study of the mouthpiece pressure waveforms for brassy and non-brassy tones showed that the modification of embouchure used by this player in passing from non-brassy to brassy timbre resulted in a delayed onset and resulting steepening of the rising edge of the waveform. The playing technique thus exploited the dependence of the non-linear wave steepening on the maximum mouthpiece pressure gradient in order to control the brightness of the sound at constant dynamic level.

Simulations carried out using weak non-linear shock theory and the harmonic balance technique confirmed that, although the frequency dependence of the linear transfer function from internal to radiated pressure did contribute significantly to the change in timbre, the major factor in the spectral enrichment was non-linear propagation and wave steepening.

Although some players have observed that it is possible to control onset of brassiness through embouchure manipulation, the exact mechanism used by the player to modify the mouthpiece pressure waveform has not yet been identified. It is likely that manipulation of the embouchure, including a combination of changes to the mechanical parameters of the lip valve and adjustments to the acoustical parameters of the mouth cavity are involved. Studies using a transparent mouthpiece and a high speed digital camera may help to explain how some brass instrument players are able to exercise this subtle but musically important form of timbral variation.

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[5] R. W. Pyle: The effect of wall materials on the timbre of brass instruments. Proc. 16th International Congress on Acoustics and 135th ASA Meeting, Seattle, 1998, III, 751–752.

[6] R. W. Pyle: Does a brass-instrument's timbre depend on the alloy from which it is made? 135th JASA Meeting, Portland, 2009.

[7] D. M. Campbell, C. A. Greated: The musician's guide to acoustics. Oxford University Press, New York, 1987.

[8] D. M. Campbell: Brass instruments as we know them today. Acta Acustica united with Acustica **90** (2004) 600–610.

[9] J. Gilbert, L. Menguy, D. M. Campbell: A simulation tool for brassiness studies. J. Acoust. Soc. Am. **123** (2008) 1854–1857.

[10] A. H. Benade: Fundamentals of musical acoustics. 2nd edition. Dover, 1990.

[11] M. F. Hamilton, D. T. Blackstock: Nonlinear acoustics. Academic Press, New York, 1998.

[12] P. Farkas: The art of french horn playing. Summy-Birchard, 1956.

[13] J. Menguy, J. Gilbert: Weakly nonlinear gas oscillations in air-filled tubes; solutions and experiments. Acta Acustica united with Acustica **86** (2000) 798–810.

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LISA NORMAN, ARNOLD MYERS, AND MURRAY CAMPBELL

Wagner Tubas and Related Instruments: An Acoustical Comparison

Many references to the Wagner tuba, historically and currently, dwell on both its notoriety as a fiendishly difficult instrument to play well in tune, and also its unique dark and sonorous timbre. The latter praise is often given to justify the former foibles. But 'dark' and 'sonorous' are just words, which by their very nature are difficult to quantify, and what exactly is it about the Wagner tuba that makes it so difficult to play? An objective approach such as that offered by acoustical analysis could provide a useful method for exploring some of these issues.

The study of brass instrument acoustics is an exciting area in which to research as there is still much to be learned about what influences timbre. The Wagner tuba has yet to be examined in any detail and so this article is proposed as an initial foray into the acoustical identity of the Wagner tuba, providing a broad comparison with related instruments, and also looking more closely at what influences the response, timbre and intonation of a specific instrument. This article reports on acoustical tests that measure the input impedance, and brassiness experiments involving the excitation of instruments with an increasingly loud sine wave tone. Based on these measurements, information about both the linear and non-linear response of an instrument, its intonation, and timbre is discussed with reference to variation in the physical measurements of the bore profile. The word brassiness is used here to denote the change in tone quality that occurs on some brass instruments when played at a loud dynamic level.

Instruments examined in this study include a number of different models of Wagner tuba by makers Alexander, Mahillon, Moritz and Schopper, spanning the twentieth century. Instruments by the maker Mahillon have been included in the list of 'Wagner tubas' because this is how they are most commonly described, although this description is perhaps slightly deceptive; their bore profile is arguably more closely aligned to that of the trombone than the Wagner tuba, and the mouthpiece receiver fits a trombone-like mouthpiece, rather than the narrower shank of the horn mouthpiece most commonly used with Wagner tubas. John Webb makes this point in his informative article, 'Mahillon's Wagner Tubas', which inspired this research into the identity of the Wagner tuba.[1] Other related instruments examined in this survey include cornophones and baritones. A list of the instruments included in this study is given in the Appendix.

INPUT IMPEDANCE

The acoustic input impedance provides an indication of the response of an instrument as a function of frequency and can be measured using the commercially available Brass Instrument Analysis System (BIAS).[2] There are two small microphones

[1] John Webb, 'Mahillon's Wagner Tubas', *Galpin Society Journal* 49 (March 1996), pp. 207–212.

[2] Gregor Widholm, 'Brass Wind Instruments Quality Measured and Evaluated by a new Computer System', *Proceedings, 15th International Congress on Acoustics, Trondheim*, (1995), Vol. III, pp. 517–520.

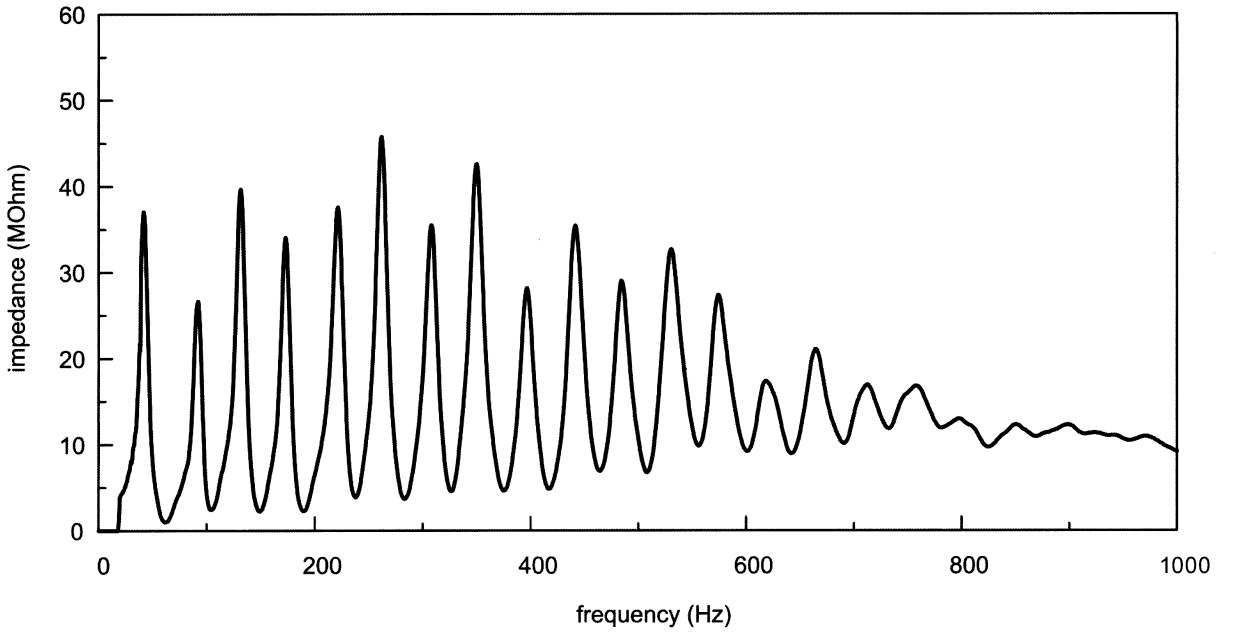

Figure 1. *Input impedance curve for EUCHMI (2516), Wagner tuba in 12-ft F by Alexander, Mainz, early 1930s (horn mouthpiece used - PHC22).*

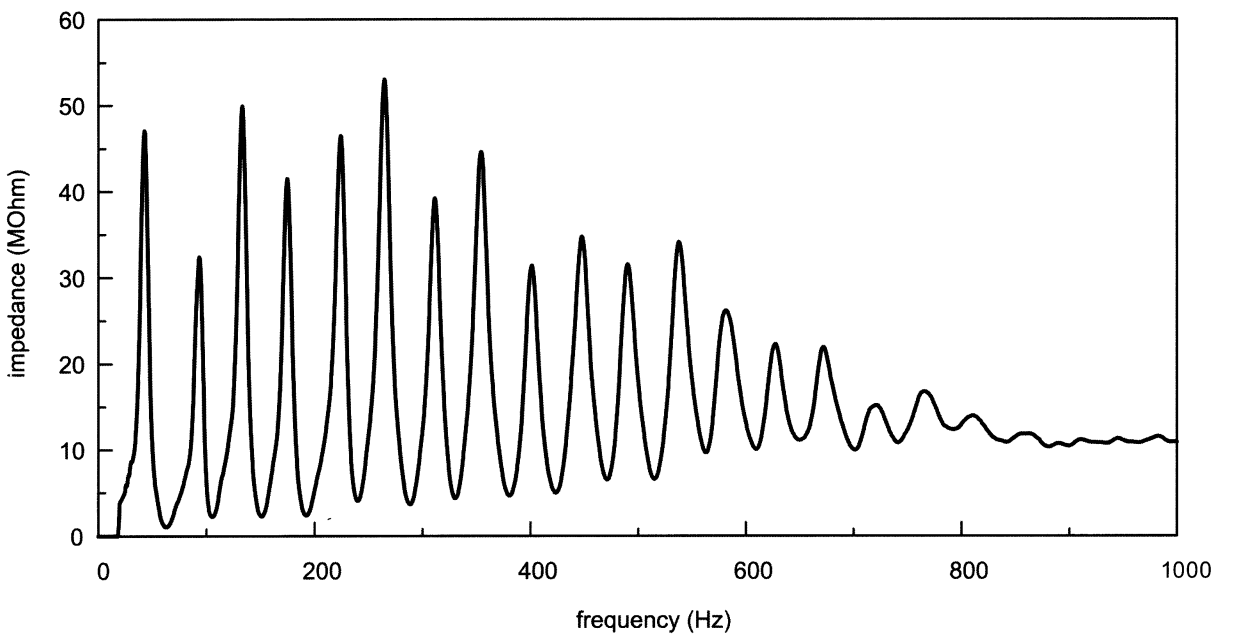

Figure 2. *Input impedance curve for EUCHMI (2855), Wagner tuba in 12-ft F by Alexander, Mainz, early 1930s (horn mouthpiece used - PHC22).*

within the measuring head positioned at either end of a high-impedance capillary (over which the mouthpiece is positioned). These microphones measure the sound pressure, while a loudspeaker, also enclosed in the measuring head, emits a frequency sweep referred to as a chirp. The BIAS system analyses this data and produces a graph of the input impedance.

A significant advantage of using BIAS or similar measurement techniques is that they are non-invasive and require little contact with the instruments. Brass instruments are perishable and curators of public collections are becoming increasingly sensitive to issues of excessive handling and contact.

SIMILARITIES AND DIFFERENCES

Figures 1 and 2 show the input impedance curves for two Wagner tubas with nominal pitch 12-ft F. The maximum values and the sharpness of the peaks provide an indication of the frequencies at which steady tones can most easily be produced. These represent the natural modes of resonance for

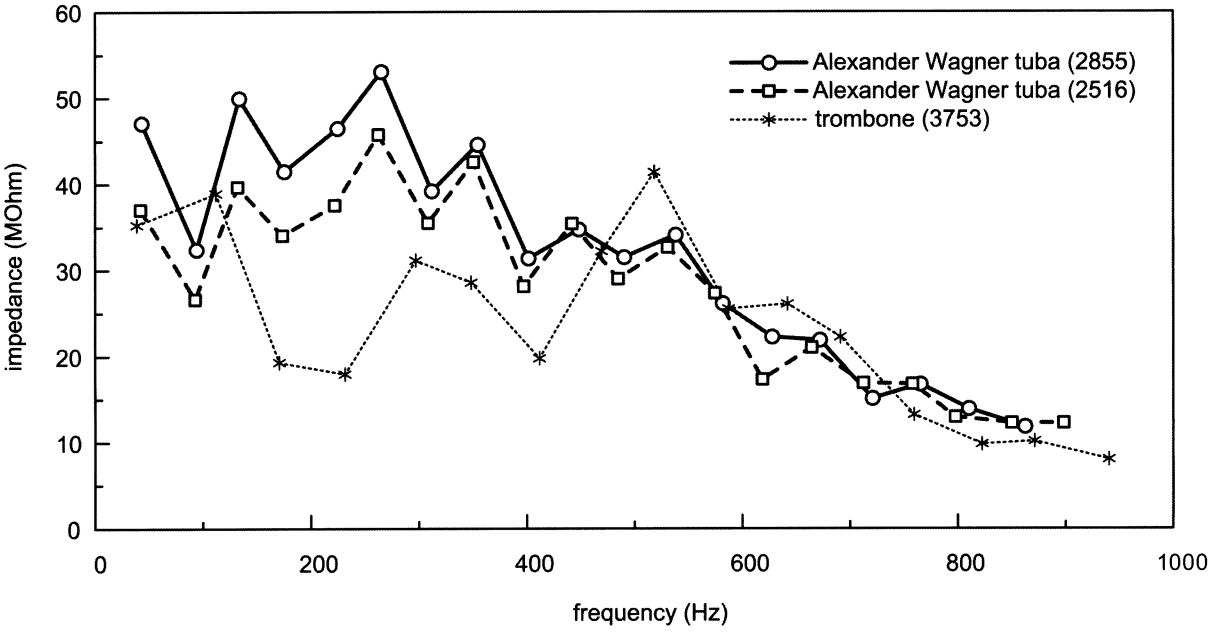

Figure 3. *Peak envelopes of the input impedance curves for the two instruments as shown in Figures 1 and 2, EUCHMI (2516) and (2855), Alexander Wagner tubas in 12-ft F, and also a trombone EUCHMI (3753) for comparison (horn mouthpiece used for Wagner tubas - PHC22; mouthpiece used for trombone - EUCHMI (1586)).*

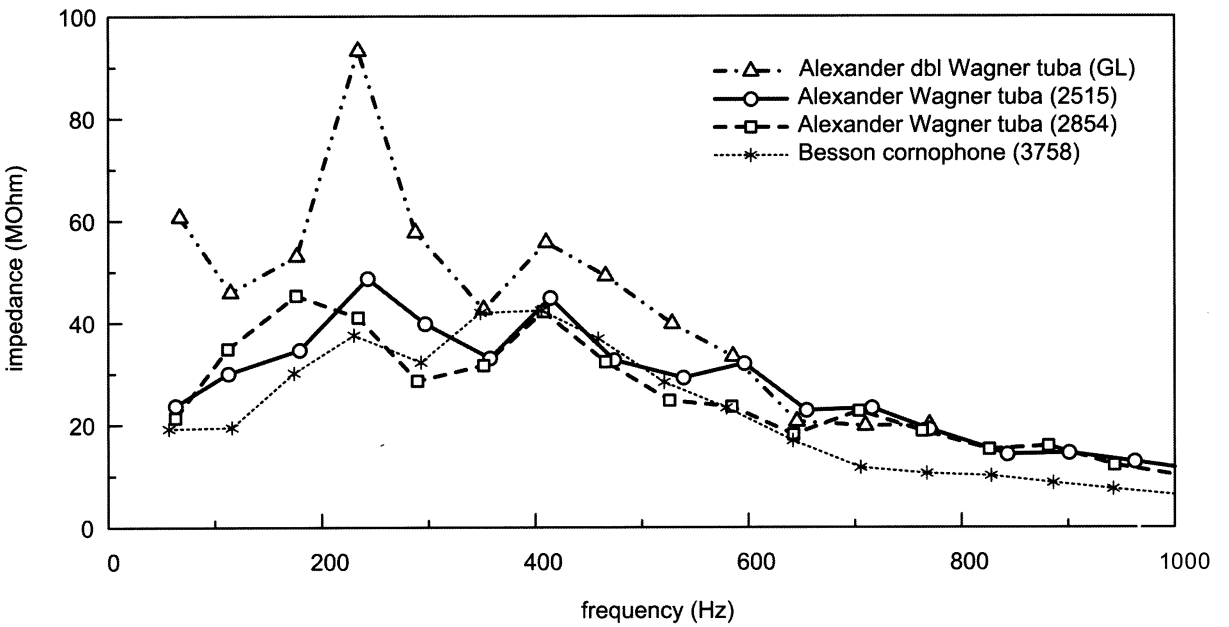

Figure 4. *Peak envelopes of the input impedance curves for EUCHMI (2515) and (2854), Alexander Wagner tubas in 9-ft B-flat; GL (1), Alexander modern double Wagner tuba; EUCHMI (3758), Besson cornophone in 8-ft C (1st valve depressed) (for Wagner tubas, horn mouthpiece used: PHC22; mouthpiece used for cornophone: EUCHMI (3759)).*

a particular instrument and are normally found to be a close approximation to the musically useful harmonic series.

It must be noted that the response curve shows the impedance of the instrument in its present state with dents and dust etc., and may be different from its impedance when it was in its original, brand new state. In spite of this, it is encouraging to see that the two graphs (Figures 1 and 2) share very similar curves as might be expected given that they are an associated pair of bass tubas from a full set of four (two tenors, two basses) and were most likely built to the same specifications.

The similarities in the curves can be seen more

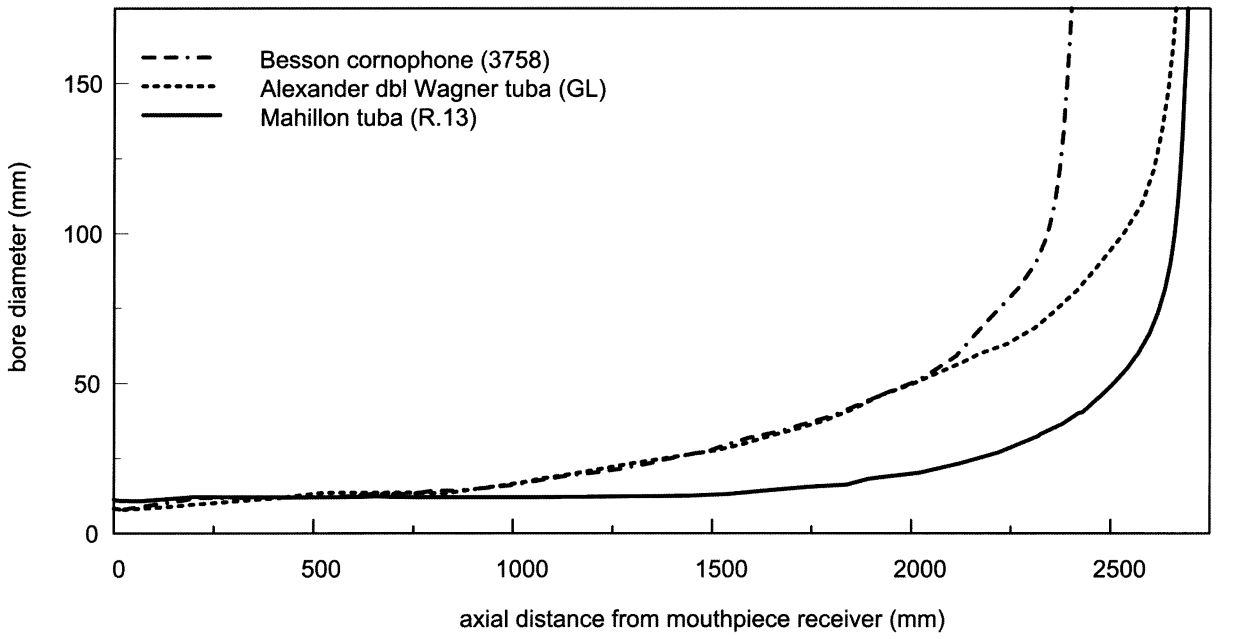

Figure 5. *Bore profiles, excluding final part of bell flare, for the Besson cornophone in C (EUCHMI 3758), the Alexander double Wagner tuba, 'B-flat side' (GL 1), and the Mahillon tuba (MIM R.13).*

easily by plotting just the peak values themselves, and creating a graph of the peak envelopes,[3] see Figure 3. Although information about the sharpness of each impedance peak is missing from this graph, the vital information, which allows us to distinguish between different types of instrument, lies mainly in the overall shape of the impedance curve. To put the variation in the shapes of impedance curves in context, the peak envelope for a trombone has also been included.

Interestingly, the cornophone in C by Besson shares a similar curve to the pair of nominally pitched B-flat Alexander Wagner tubas, the peak envelopes for which can be seen in Figure 4. The graphs show peaks in the shapes of their envelopes in the region of 225 Hz and then again at approximately 400 Hz. The modern double Wagner tuba impedance curve also follows this shape but the values are significantly higher overall, particularly that of the fourth mode of resonance. When playing this instrument there is no noticeable difference in response between this high amplitude resonance (at approximately 225 Hz) and that of the ones on either side. It would appear that it is the pattern of stronger and weaker resonances which plays the more crucial role in determining the response of an instrument, rather than the heights of specific peaks. The higher impedance amplitudes of the double Wagner tuba peaks could perhaps be due to the internal condition of the new instrument, compared with that of the older instruments.

The similarity in impedance would suggest that these instruments also share similar bore profiles, the dominant factor in influencing acoustic response. The graph in Figure 5 compares the bore profiles for the Alexander double Wagner tuba, GL (1), and the Besson cornophone, EUCHMI (3758). Approximately the first three quarters of the tube dimensions show a strong similarity, after which point the two curves diverge; this is because the cornophone, pitched in 8-ft C, is about 230 mm shorter than the Wagner tuba in 9-ft B-flat. The similarity between cornophone and Wagner tuba is highlighted by the very different bore profile of the Mahillon tuba (also shown in Figure 5).

ROLE OF THE MOUTHPIECE

The role of the mouthpiece plays an important part in the response of any brass instrument; it has a resonance of its own, which is largely dependent on the cup volume and throat dimensions. For trumpets in particular, the mouthpiece resonance plays a key role as it helps to strengthen the natural modes of the air column at around this resonance frequency. For other brass instruments, especially those with a predominance of expanding tubing, such as tubas, the role of the mouthpiece is somewhat different in that the strengthening of the natural resonant modes occurs at a value below the resonance

[3] René Caussé, Jean Kergomard, and Xavier Lurton, 'Input impedance of brass musical instruments – comparison between experimental and numerical models', *Journal of the Acoustical Society of America* 75, no. 1 (1984), pp. 241–54.

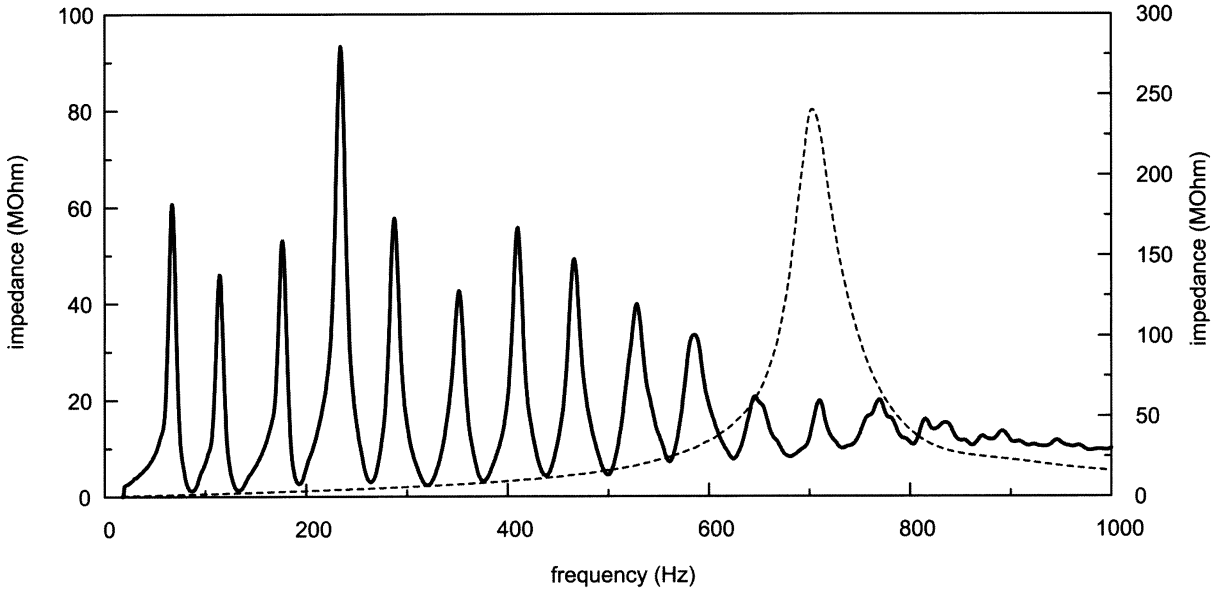

Figure 6. *Input impedance curve for GL (1), Alexander double Wagner tuba, B-flat side (solid line – scale on left), with a typical horn mouthpiece, PHC22 (dashed line – scale on right).*

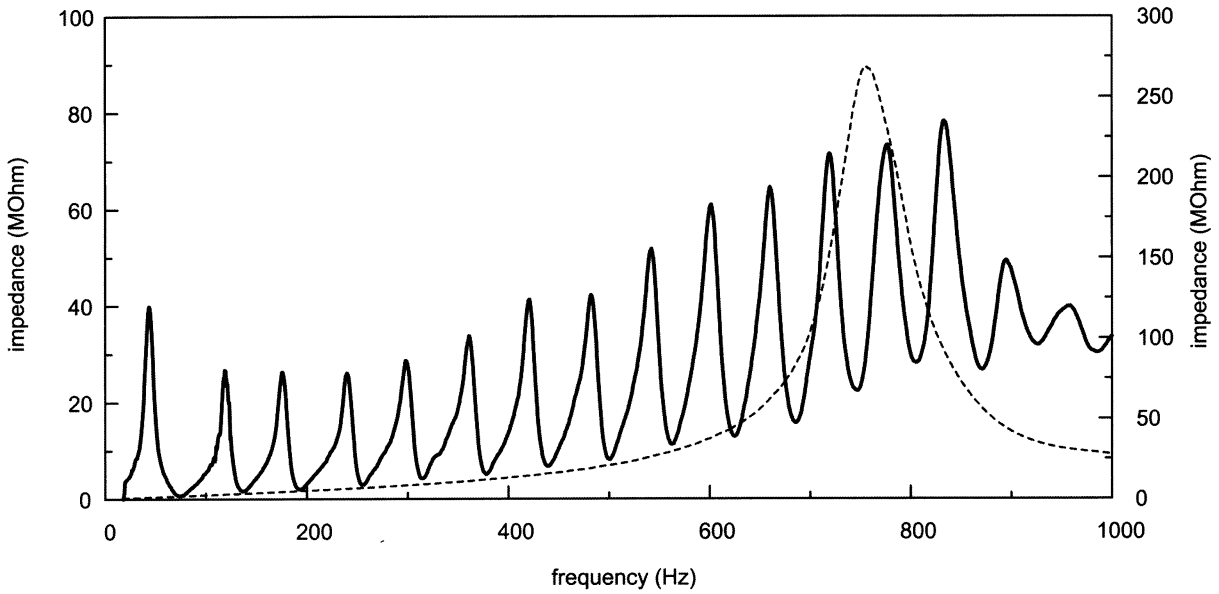

Figure 7. *Input impedance curve for MIM (R.13), Mahillon tuba in B-flat (solid line – scale on left), with a cupped mouthpiece (dashed line – scale on right).*

frequency of the mouthpiece.[4] This was the case in all the examples shown below. For example, Figure 6 shows the impedance curve for the double Wagner tuba (B-flat side) with the input impedance curve for the mouthpiece that was used in the measurement superimposed.

An example of an input impedance curve for which the maximum peak value of the response curve corresponds to the resonance of the mouthpiece can be seen in the curve for the Mahillon tuba (MIM (R. 13)) in Figure 7. There are very strong peaks at around 800 Hz, which correspond to the resonance of the mouthpiece. The lower modes are considerably weaker which suggests that the player would experience a noticeable contrast in the response of the instrument over its range. The mouthpiece used for this experiment had a rather shallow cup and narrow throat, similar to that of a typical trumpet mouthpiece. Perhaps a deeper, slightly more funnel shaped mouthpiece would suit this instrument better if it were used to play the lower Wagner tuba parts.

[4] Caussé, 'Input impedance of brass musical instruments', p. 250.

INTONATION

Players often complain about the intonation of the Wagner tuba and some authors have suggested that the problem is largely due to the great difference in diameter between the narrow mouthpipe and the wide bell.[5] Others believe that the issue lies more with the horn players themselves, who are so used to making small adjustments with the hand in the bell, often almost subconscious movements, that when they are suddenly faced with an upward pointing bell, they find the technique quite different. This problem is exacerbated by the fact that horn players often have only a limited amount of time in which to practise the instrument, as the majority of players do not own their own Wagner tubas. Instead they must make do with unfamiliar borrowed instruments from institutions or orchestras.

The process of comparing whether one instrument has better or worse intonation than another is a slightly problematic area as there are a number of different factors which influence the tuning of a brass instrument, including:

- specific player technique
- mouthpiece dimensions
- snugness and depth of fit of mouthpiece into the mouthpipe
- temperature of air inside the instrument
- dynamic level

Large differences in intonation can easily be detected by the player, but the finer issues of tuning within a musical context introduces more subjectivity, and it is useful to consider a more objective method for analysing intonation.

One approach is to look at information drawn from the input impedance measurements. The peak values tell us the strength and frequency of each of the natural modes of resonance. The pitch deviation of each resonance from a harmonic series based on the 'equivalent fundamental pitch' of the instrument (EFP) can then be plotted. The EFP is a calculation of the fundamental frequency of a particular mode relative to a reference pitch, in this case based on the average of the fourth and eight modes of resonance. When all resonant modes are plotted, in Figure 8 for example, the closer they are to forming a straight, vertical line, the more harmonically related they are, helping to provide some indication of how well in tune an instrument is. For the sake of comparison, the following examination looks only at 'open' notes, i.e. without valves one, two, three or four operated.

MODERN DOUBLE WAGNER TUBA

Figure 8 shows the EFP plot for a modern double Wagner tuba (GL (1)) measured on the 'F side'. It appears to be well in tune as the modes of resonance are very close to being harmonically related. Interestingly, if we look at the modes within the normal range of playing (modes 2 to 12), a slight deviation occurs on mode 7. As a member of the harmonic series, the pitch of this mode does not naturally fit into our modern system of equal temperament; the 7th is too flat. It so happens therefore, that this note would nearly always be played on alternative fingering anyway and so it does not matter greatly that it is slightly wayward.

Another deviation occurs on the 2nd mode, an octave below middle C (as written for tuba 'in F'), which is approximately a semitone sharp (100 cents) compared with the other resonances. Although this may seem initially problematic, in reality it is not such an issue; with some practice, the note can be played in tune because its upper harmonic components (modes 4, 6, 8, etc.) support the note at a pitch relative to the tuning of their respective resonances.

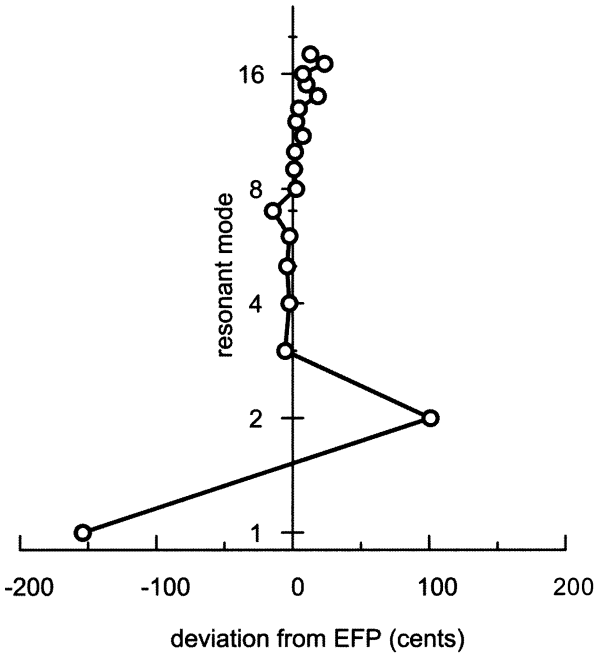

Figure 8. *Equivalent fundamental pitches for modes with significant impedance peaks for GL (1), Alexander double Wagner tuba, 'F side'.*

[5] Richard Merewether, *The Horn, The Horn...* (London: Paxman, 1978), pp. 14-16; and Barry Tuckwell, *Horn* (London & Sydney, 1983), pp. 90-91.

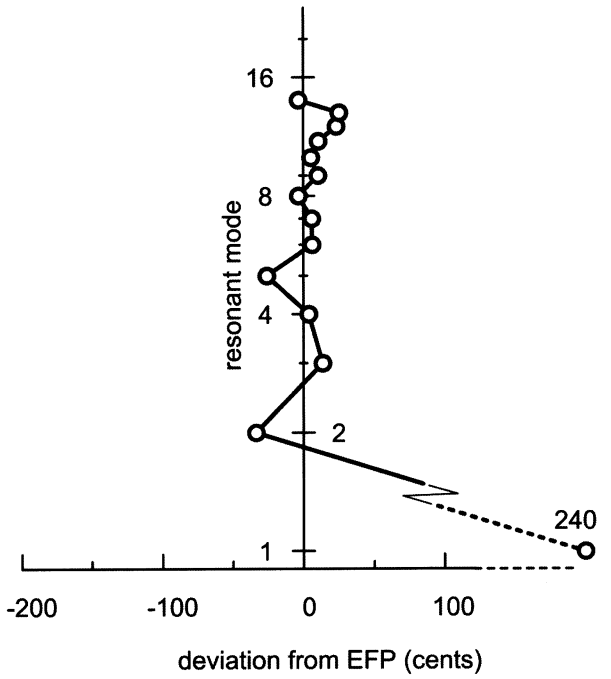

Figure 9. *Equivalent fundamental pitches for modes with significant impedance peaks for GL (1), Alexander double Wagner tuba, 'B-flat side'.*

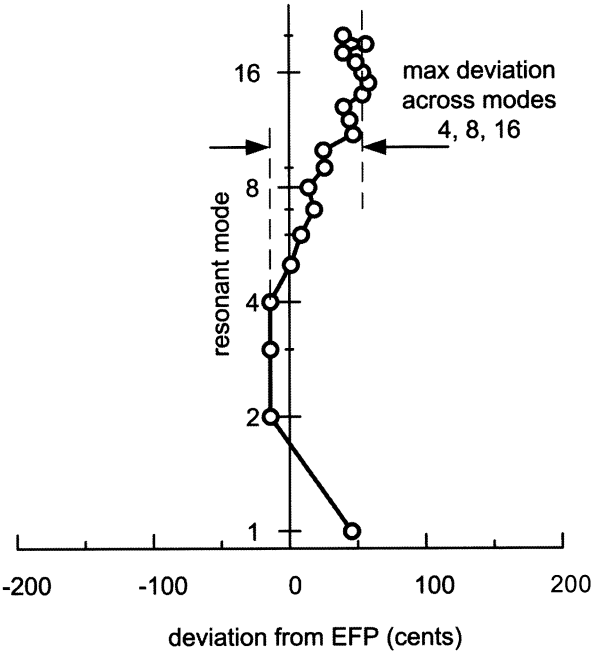

Figure 10. *Equivalent fundamental pitches for modes with significant impedance peaks for MIM (JT205), Červený euphonium, in B-flat with no valves operated The maximum deviation across modes 4, 8 & 16 is also shown.*

Thus the pitch of the 2nd mode of resonance, when played, sounds much flatter than it appears on the graph. This is due to the phenomenon of cooperative regimes of oscillation.[6] It is also significant that this resonance is extremely weak (apparent from impedance measurements) and therefore exerts very little influence on the pitch of the note. Practical playing tests confirmed that although this note did not feel as well 'centred' as some of the higher pitches, with adequate breath support and pitch awareness, it could be played in tune.

Figure 9 shows an EFP plot for the same instrument (double Wagner tuba) but with measurements taken on the 'B-flat side'. In comparison with the 'F-side' the intonation on the 'B-flat side' is slightly more erratic. When playing a brass instrument in its lower register, the lips generally receive more support, due to cooperative regimes of oscillation, than when it is played in its higher register. Increasingly less support is available as the upper harmonic resonances become weaker; in Figure 9, for example, mode 7 is supported to some extent by its second harmonic, mode 14, but there is no significant resonance at the 16th mode to provide similar support for mode 8. Therefore this, and higher modes largely rely on the strength and tuning of the fundamental alone. In the EFP plot in Figure 9, it could be predicted that the 12th mode might prove difficult to play in tune because it is a weak, slightly sharp resonance with no support from higher harmonics.[7]

SHAPE OF PLOTS

The shape of EFP plots can vary significantly depending on the type of instrument. Figure 10 shows a slightly curved plot for the Červený euphonium in B-flat (MIM (JT205)). Of all the instruments measured, the Červený euphonium has the most 'conically' shaped bore profile. It must be noted that the term 'conical' here is not used in the strictest sense of the word; the euphonium, like the majority of valved brass instruments, has a section or sections of cylindrical tubing, but overall it has a far greater proportion of expanding tubing than more cylindrical instruments such as the trumpet or trombone. One of the ways in which 'conically' shaped instruments differ from their more cylindrical counterparts, is that their lowest modes of resonance are closer to the desired pedal note frequencies and this is one reason why low brass instruments are commonly made of predominantly

[6] Neville H. Fletcher and Thomas D. Rossing, *The Physics of Musical Instruments* (New York: Springer, 1998), pp. 139–140.

[7] This pitch is required of the tenor tuba player in the last act of *Das Rheingold*.

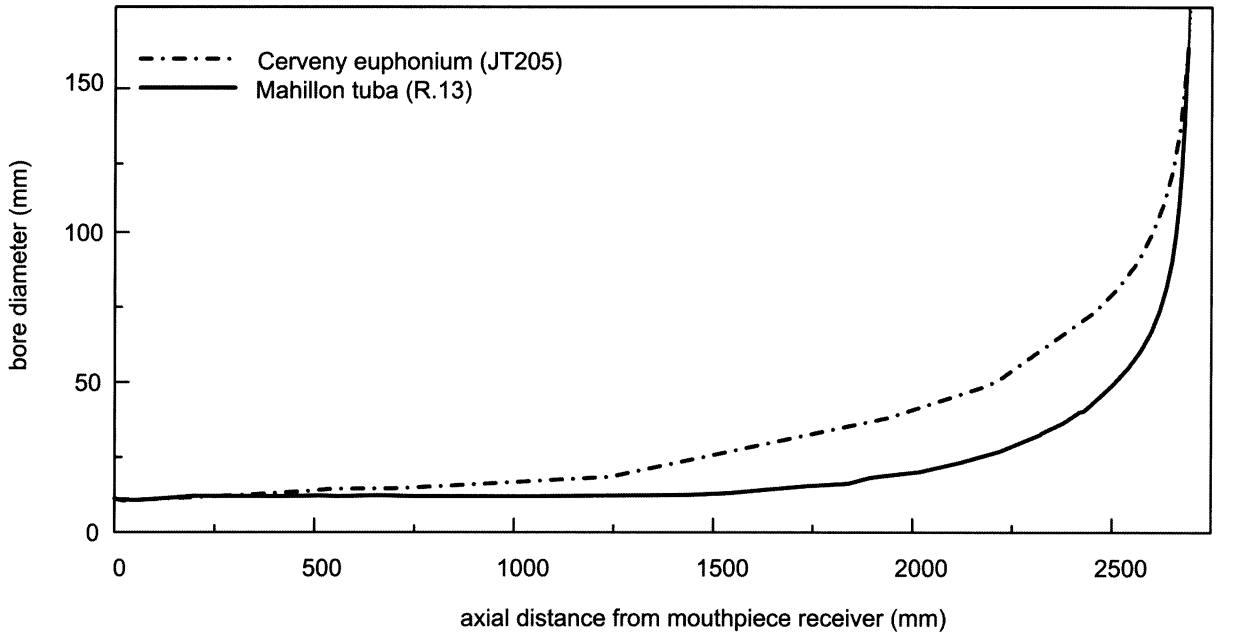

Figure 11. *Bore profiles, excluding final part of bell flare, for the Červený euphonium in B-flat (MIM JT205) and the Mahillon tuba in B-flat (MIM R.13).*

conical, or expanding tubing.[8] In Figure 10, the 1st mode for the Červený euphonium is less than a semitone sharp and the 2nd mode is in line with those immediately higher.

In contrast, the Mahillon tuba is more cylindrical in shape than the other instruments measured, and in this respect is similar to the trombone as discussed in the introduction. The graph in Figure 11 shows the contrast between the bore profiles of the Mahillon tuba and the Červený euphonium. Looking at the EFP plot for the Mahillon tuba in Figure 12, we can see that the first mode of resonance is extremely flat, a common characteristic of more cylindrical instruments.

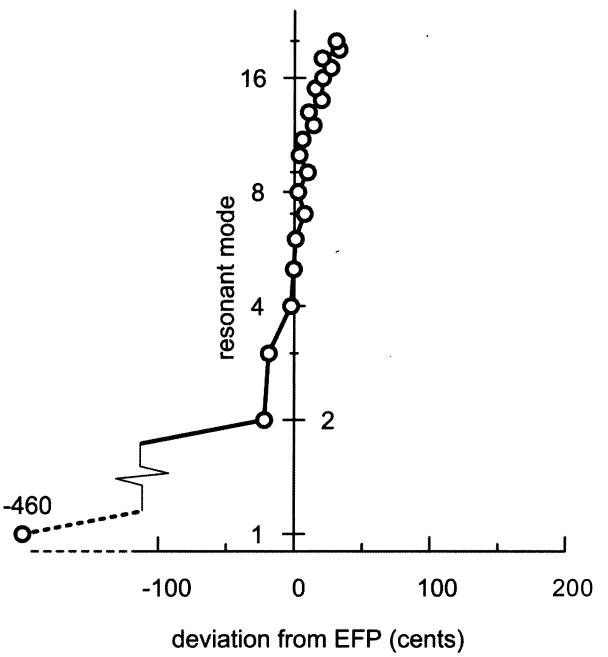

Figure 12. *Equivalent fundamental pitches for modes with significant impedance peaks for EUCHMI (5833), Mahillon tuba, in F with no valves operated.*

The bore profiles of Wagner tubas generally fall somewhere in between the shape of the euphonium and horn. Examination of a number of EFP plots for the Wagner tuba reveals that they are generally characterised by erratic tuning below the 4th mode of resonance with more harmonic alignment in the higher modes. However, there did appear to be a significant degree of variation among the instruments measured (even within the same instrument when a substantial amount of tubing was introduced via a valve). Instruments such as the modern double Alexander Wagner tuba (GL (1)) were found to have much greater harmonicity among their modes of resonance than the older models of Alexander Wagner tuba from the 1930s (EUCHMI (2515, 2516, 2855, 2856)). The cornophones appeared to have the most erratic tuning of all.

OCTAVE COMPARISONS

The two tables below (Tables 1 and 2) show the deviation in cents over a range of three octaves for a number of different instruments with no valves depressed. (All measurements have been rounded to

[8] Arthur Benade, *Fundamentals of Musical Acoustics* (New York: Dover, 1976), p. 411.

Table 1. *Deviation in cents of a number of 12/13-ft instruments based on a reference fundamental pitch of the average of modes 4 and 8. Deviation across mode numbers 4, 8 & 16 are also listed.*

12/13-ft instruments		mode number				max deviation across modes 4, 8, 16
		2	4	8	16	
Alexander double tuba	GL (1)	+100	- 3	+2	+5	8
Schopper tuba	EUCHMI (1677)	+2	-3	+3	-8	11
Moritz tuba	EUCHMI (5892)	+24	+11	-12	+6	23
Mahillon tuba	EUCHMI (5833)	-18	-3	+3	+22	25
Fuchs Vienna horn	EUCHMI (4461)	-61	-17	+16	+15	33
Alexander tuba	EUCHMI (2516)	+95	-10	+9	+40	50
Alexander tuba	EUCHMI (2855)	+102	-13	+12	+38	51
Besson cornophone	EUCHMI (4208)	+27	-18	+19	+68	86

the nearest cent.) Instruments are separated into two groups — longer instruments (Table 1) and shorter instruments (Table 2) — and are ranked according to the variation across only mode numbers 4, 8 and 16 (column on the far right). Mode number 2 is not taken into account, as it has no influence over the tuning of modes higher than itself. An example of this maximum deviation can be seen on the EFP plot for the Červený euphonium in Figure 10. The aim of the maximum deviation parameter is to provide a general indication of the harmonicity and relative tuning of the instruments. Modes 2, 4, 8 and 16 were chosen for investigation, as they are, generally speaking, normally played without the use of valves on most brass instruments and correspond to intervals of an octave, represented by the ratio 2:1.[9] This interval is fundamental in the tuning of any instrument, as it remains pure no matter what musical temperament is in use. It is the interval many musicians use as a starting point when tuning their instruments.

The values in the tables are based on the data from the input impedance curves, and the reference point from which the deviation in cents is calculated is taken as the fundamental frequency of the average pitch of resonant modes 4 and 8 (as was the case in the EFP plots). The Wagner tuba is rarely required to play the 16th mode of resonance, but it has been included here because it plays a very important role in the tuning of the lower modes, particularly at high dynamic levels. A Vienna horn and a trombone of the sort that might have been played in performances of the Ring at the end of the nineteenth, early twentieth century are also included for comparison.

The modern double Wagner tuba comes near the top of the list on both tables which would suggest that it has the potential to play well in tune. The cornophones however, perform relatively poorly in this ranking system, as their 16th resonances are generally very sharp compared with the lower modes. The inharmonicity of these instruments, observed as an upward drift in pitch of more than 40 cents (75 cents for the cornophone (EUCHMI 4509)) between modes 8-16, results in a less focused response in the

Table 2. *Deviation in cents of a number of 8/9-ft instruments based on a reference fundamental pitch of the average of modes 4 and 8. Deviation across mode numbers 4, 8 & 16 are also listed.*

8/9-ft instruments		mode number				max deviation across modes 4, 8, 16
		2	4	8	16	
Mahillon tuba	MIM (R.13)	-19	- 4	+3	-11	14
Alexander double tuba	GL (1)	-36	+3	-3	+21	24
Alexander tuba	EUCHMI (2854)	+-75	+5	-6	+19	25
Mitsching-Alschausky trombone	EUCHMI (3753)	-74	-14	+13	+18	32
Besson cornophone	EUCHMI (3758)	-49	+1	-1	+40	41
Alexander tuba	EUCHMI (2515)	-113	+22	-22	+1	44
Červený euphonium	MIM (JT205)	-21	-13	+14	+51	64
Besson cornophone	EUCHMI (4509)	-62	-6	+7	+82	88

[9] For a note of given frequency, each subsequent higher octave is twice the frequency of the previous pitch, hence the ratio 2:1.

lower and middle registers as these notes are lacking the support from higher 'in-tune' harmonics.

The data set is relatively small and many more instruments would be required in order to draw more substantive conclusions. It would also be valuable if future research investigated the intonation of different valve combinations. Nevertheless, the values in these tables suggest that Wagner tubas do not appear to have particularly erratic intonation when compared to examples of other instruments such as the cornophone, baritone, horn and trombone.

BRASSINESS

One of the most characteristic aspects of the sound of a brass instrument is the rate of spectral enrichment with increasing dynamic level, i.e., how brassy the tone becomes during a crescendo. This can vary considerably depending on the bore profile of the instrument. Previous research into this brassiness characteristic has involved the analysis of crescendos, performed by human players, and was based on the comparison of a parameter called the normalised spectral centroid, SC:[10]

$$SC = \frac{\sum_n n.P_n}{\sum_n P_n}$$

where P_n is the pressure amplitude of the n^{th} harmonic component in the radiated sound. The spectral centroid is a measure associated with the brightness of a sound and is a calculation of the weighted mean of the harmonics present in the signal, where the weighting corresponds to the magnitude of the pressure amplitudes, *P*. It can be likened to the 'centre of gravity' of the tone. The dominant factor influencing the rate of spectral enrichment has been found to be the bore profile,[11] but mouthpiece dimensions,[12] construction material of the instrument,[13] and embouchure manipulation,[14] have also been cited as affecting the timbre.

In the tests mentioned, the element of human control introduces a certain degree of subjectivity to the measurements and so in this study, a similar procedure has been carried out, but using a loudspeaker as the excitation mechanism rather than the human players' lips. The experiments were carried out in an anechoic chamber and the relationship between the initial sound pressure waveform produced by the loudspeaker at the entrance to the instrument and the resulting radiated sound pressure waveform from the bell was measured using two appropriately positioned microphones. The loudspeaker was controlled via a computer interface card and was set to emit a crescendo of a sinusoidal tone. The spectral centroids for the input (SC_1) and radiated (SC_2) pressure signals were then calculated and SC_2 was plotted as a function of the rms pressure of the input signal, P_1, in order to produce a 'brassiness' curve. Where limited spectral enrichment occurs in an instrument (i.e. the sound does not have the potential to become particularly brassy), SC_2 remains close to a value of 1 when excited at increasingly high pressure levels. At the other end of the scale, instruments with the greatest brassiness potential produce the largest increase in SC_2 when similarly excited.

INSTRUMENTS IN 12-ft F OR 13-ft E-flat

Figure 13 shows the brassiness curves for the longer instruments. Interestingly, there is a notable spread in the shape of the curves within the group of instruments that could be classified as 'Wagner tubas' (bold lines); the Schopper tuba shows the greatest increase in SC_2 while the Alexander tuba (EUCHMI 2855) reveals the least brassiness potential.

Reasons for this difference could include the fact that the Schopper instrument has a relatively rapid mouthpipe expansion followed by a long, approximately cylindrical section of about 700 mm

[10] Joël Gilbert, Murray Campbell, Arnold Myers and Robert Pyle, 'Differences between brass instruments due to nonlinear propagation', *Proceedings, International Symposium on Musical Acoustics, Barcelona* (September, 2007).

[11] Arnold Myers, Joël Gilbert, Robert Pyle and Murray Campbell, 'Non-linear propagation characteristics in the evolution of brass musical instrument design', *Proceedings, 19th International Congress on Acoustics, Madrid, Spain* (September, 2007).

[12] Emilie Poirson, Jean-François Petiot and Joël Gilbert, 'Study of the brightness of trumpet tones', *Journal of the Acoustical Society of America* 118 (4) (October, 2005), pp. 2656–2666.

[13] Robert Pyle, 'The effect of wall materials on the timbre of brass instruments', *Proceedings, 16th International Congress on Acoustics and 135th JASA Meeting*, v.3, Seattle (1998), pp. 751–752; and also, Robert Pyle, 'Does a brass-instrument's timbre depend on the alloy from which it is made?', *135th JASA Meeting, Portland* (April, 2009).

[14] Lisa Norman, John Chick, Murray Campbell and Arnold Myers, 'Embouchure control of brassiness at constant pitch and dynamic level in orchestral horn playing', *Proceedings, NAG/DAGA International Conference on Acoustics, Rotterdam* (March, 2009).

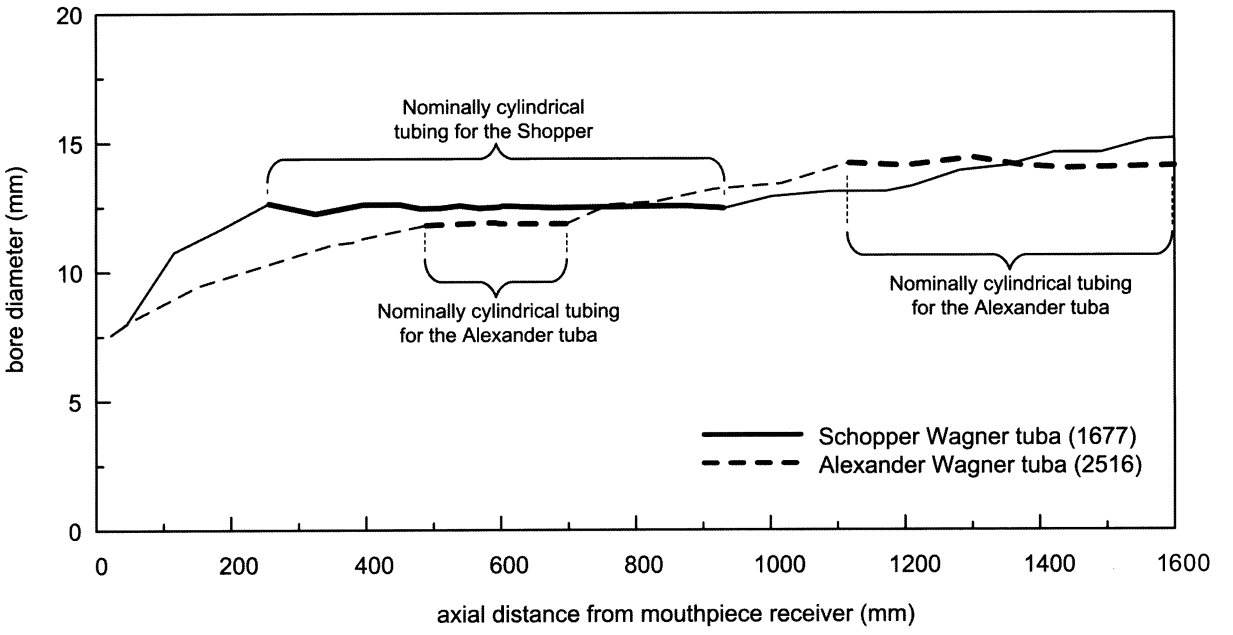

Figure 14. *Bore profiles, showing only approximately the first half of the tubing, for the Schopper Wagner tuba in F (EUCHMI 1677) and the Alexander Wagner tuba (EUCHMI 2516).*

at a bore diameter of around 12.5 mm. If we compare this with the Alexander tuba (EUCHMI 2516) we find that the initial expansion of the mouthpipe is much more gradual, leading to a short cylindrical section of approximately only 200 mm, followed by further expansion and then another cylindrical section of 500 mm with a bore diameter of about 14 mm, see Figure 14.

Perhaps the most important factor to influence the non-linear behaviour of the waveform in an instrument's air column, and thus its potential brassiness, is the diameter of the cylindrical or near cylindrical tubing; in the example above, although both instruments have approximately the same length of cylindrical tubing (700 mm), the average diameter of that of the Schopper instrument is narrower, allowing for greater non-linear behaviour.

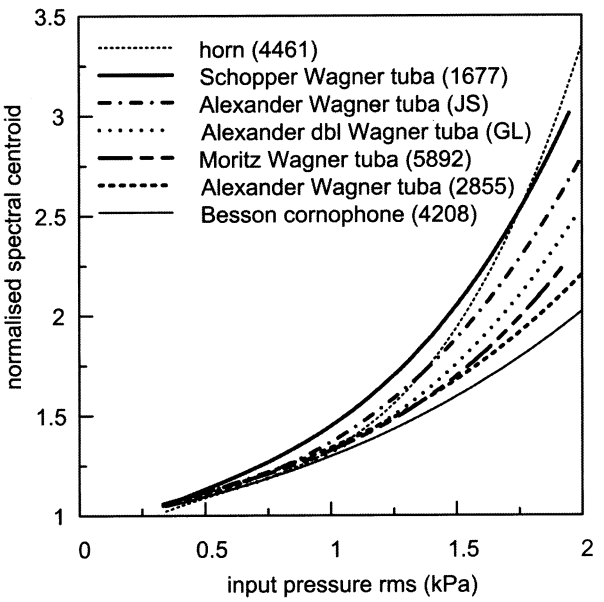

Figure 13. *Brassiness curves showing SC_2 as a function of P_1 for instruments in 12-ft F and 13-ft E-flat.*

The Besson cornophone in 13-ft C is at the lowest end of the brassy spectrum in this group (Figure 13), and indeed, the bore profile of the instrument includes only two very short sections of cylindrical tubing.

The curve most unlike the others in terms of shape is that of the Vienna horn; in comparison with the rest of the group, it has the greatest potential for brassiness, but spectral enrichment occurs more readily at higher amplitudes, while at lower amplitudes, the Schopper tuba has a noticeably higher value of SC_2 than the horn. It must be noted that the horn measurements were taken without the hand in the bell, i.e. not in the normal playing position, and it would be interesting to repeat the experiments taking into account the effect of the hand position.

Overall, these curves show a marked difference in the spectral enrichment characteristic of the horn compared with the Wagner tubas. The graph also shows that within the selection of Wagner tubas (three of which are by the same maker Alexander spanning a period of half a century) the variation is quite wide.

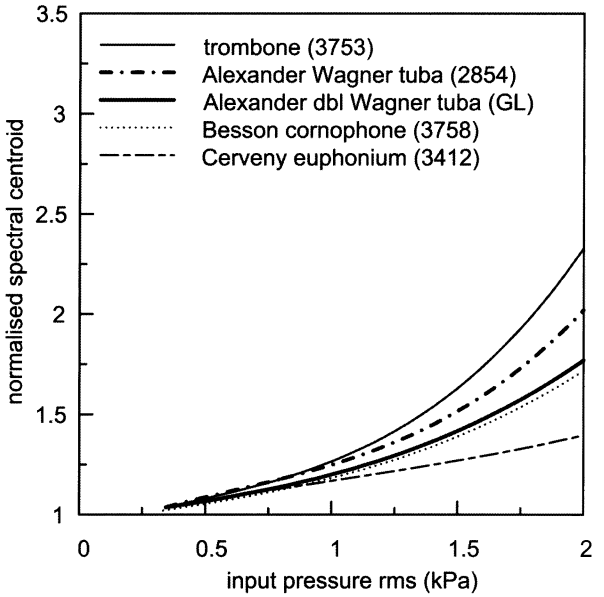

Figure 15. *Brassiness curves showing SC_2 as a function of P_1 for instruments in 8-ft C and 9-ft B-flat.*

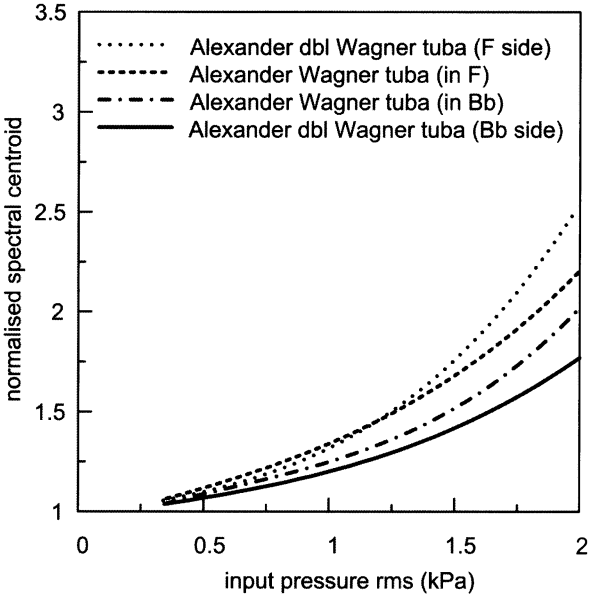

Figure 16. *Brassiness curves showing SC_2 as a function of P_1 for a double Alexander Wagner tuba (GL 1) with measurements taken on the 'F side' and 'B-flat side' of the instrument, and two associated single Alexander Wagner tubas in F (EUCHMI 2855) and B-flat (EUCHMI 2854).*

INSTRUMENTS IN 8-ft C OR 9-ft B-flat

In Figure 15, the brassiness curves for the shorter instruments in 8-ft C and 9-ft B-flat can be seen. Overall, this group of instruments has lower maximum values of SC_2 than the previous group of instruments, as would be expected since they generally have shorter lengths of narrow cylindrical tubing.

The exception to this statement is the tenor trombone, which shows greater spectral enrichment with increasing amplitude than the other instruments in this group, as we would expect due to its long cylindrical slide section. At the other end of the scale, the Červený baritone in 9-ft B-flat shows only a minimal brassiness potential, and of all the instruments, its bore profile is the most 'conical' in shape (see Figure 11). As a result, there is very little opportunity for the build up of high frequency energy due to non-linear wave propagation.

The Besson cornophone in 8-ft C shares a very similar brassiness curve to that of the 'B-flat side' of the Alexander double Wagner tuba. Earlier comparison of the bore profiles of these two instruments revealed that they also share similar dimensions, particularly for approximately the first three quarters of their tubing (see Figure 5).

THE DOUBLE WAGNER TUBA

The effect of shortening the overall length of the air column by approximately one quarter from 12-ft F to 9-ft B-flat can be seen quite clearly when comparing the results from the double Alexander Wagner tuba. For this instrument, two measurements were taken, one on the 'F side' of the instrument and the other on the 'B-flat side'; thus the proportion of cylindrical to expanding tubing is significantly less for the shorter 'B-flat side'. Figure 16 shows the difference between the two 'sides' (dotted and solid lines).

Double Wagner tuba models have come under some criticism, since they are an attempt to combine both the tenor and bass tubas in one instrument. Arguments against this design concept have often been based on the fact that some of the individuality and characteristic tone colour from either the tenor or bass instrument is lost in an attempt to combine the two bore profiles, particularly as they must share the same bell shape. Based on this theory, we would expect the graph in Figure 16 to show very little difference between the brassy curves corresponding to the two sides of the double Wagner tuba. On the other hand, we would expect the difference to be greater concerning two distinct instruments, made specifically as tenor and bass tubas. What we actually see is a very different result (Figure 16); the use of a valve on the double Wagner tuba (GL 1) to change from the 'B-flat side' to the 'F side' produces a large increase in brassiness potential, while the single bass tuba by Alexander (EUCHMI 2855) is only slightly brassier than its associated tenor tuba (EUCHMI 2854).

Table 3. *Equivalent cone length (L_{ecl}), maximum stretched coordinate value (z(L)) in (m), and Brassiness Potential parameter (B) for instruments with wide mouthpiece receiver.*

		L_{ecl} (m)	z (*L*) (m)	*B*
Mahillon tuba (in B-flat)	MIM (R.13)	2.866	1.997	0.70
Besson cornophone (in E-flat)	EUCHMI (4208)	4.502	2.353	0.52
Červený euphonium (in B-flat)	EUCHMI (3412)	3.002	1.458	0.49

Table 4. *Equivalent cone length (L_{ecl}), maximum stretched coordinate value (z(L)) in (m), and Brassiness Potential parameter (B) for instruments with narrow mouthpiece receiver.*

		L_{ecl} (m)	z(*L*) (m)	*B*
horn in the shape of a saxhorn (in E-flat)	EUCHMI (4593)	4.547	2.195	0.48
Alexander double Wagner tuba (F side)	GL (1)	3.849	1.673	0.44
Schopper Wagner tuba (in F)	EUCHMI (1677)	3.923	1.649	0.42
Alexander Wagner tuba (in F)	EUCHMI (2516)	3.966	1.626	0.41
Besson cornophone (in C)	EUCHMI (3758)	2.689	1.079	0.40
Moritz Wagner tuba (in F)	EUCHMI (5892)	4.035	1.577	0.39
Alexander Wagner tuba (in B-flat)	EUCHMI (2515)	2.875	1.089	0.38
Alexander double Wagner tuba (B-flat side)	GL (1)	2.955	1.101	0.37

BRASSINESS POTENTIAL PARAMETER

The fragile nature of historic instruments is such that it is not always possible or advisable to use them in acoustical experiments such as those described. An alternative method for predicting the potential brassiness of an instrument has been devised by Pyle and Myers,[15] and can be calculated, based on the coordinate stretching function shown in the following equation:

$$z(L) = \int_0^L \frac{D(0)}{D(y)} dy$$

where $D(0)$ is the minimum diameter in the mouthpipe of the instrument, $D(y)$ is the diameter at a distance y along the axis of the instrument, and L is the overall length of the instrument. The value of $z(L)$ is the equivalent length of cylindrical tube, of diameter $D(0)$, in which the same degree of non-linear steepening occurs as in the actual instrument of total length L.

The Brassiness Potential parameter, B, is then calculated using the following equation:

$$B = z(L) / L_{ecl}$$

where $z(L)$ is the maximum stretched coordinate value from the previous equation, and L_{ecl} is the equivalent cone length based on a fundamental frequency for a harmonic series which best fits the pitches of modes 4 and 8 of the instrument.[16]

The results have been divided into two tables according to whether the instrument has a wider (Table 3) or narrower (Table 4) mouthpiece receiver, regardless of overall length. It is encouraging that the theoretical results from the Brassiness Potential parameter calculations correlate with the experimental brassiness results discussed above.

In Table 3 the Mahillon tuba stands out as having a relatively high value of B at 0.70; this is similar to the calculation of B for trombones, carried out by Myers et al.,[17] which generally were found to fall between 0.63 and 0.80. Overall the instruments with a shorter length of tubing (9-ft B-flat) tend to come lower down in the ranking of the Brassiness Potential parameter as would be expected since the shorter instruments generally have a smaller proportion of narrow cylindrical tubing compared with their longer counterparts.

The cornophone in C does not seem out of place amongst the Wagner tubas when ranked by the

[15] This equation was taken from: Arnold Myers, Joël Gilbert, Robert Pyle and Murray Campbell, 'Non-linear propagation characteristics in the evolution of brass musical instrument design', *Proceedings, 19th International Congress on Acoustics, Madrid, Spain* (September, 2007).

[16] Murray Campbell and Clive Greated, *The Musician's Guide to Acoustics* (OUP, 2001), pp. 336–337.

[17] Myers et al., 'Non-linear propagation characteristics', *Proceedings, 19th International Congress on Acoustics, Madrid, Spain* (September, 2007).

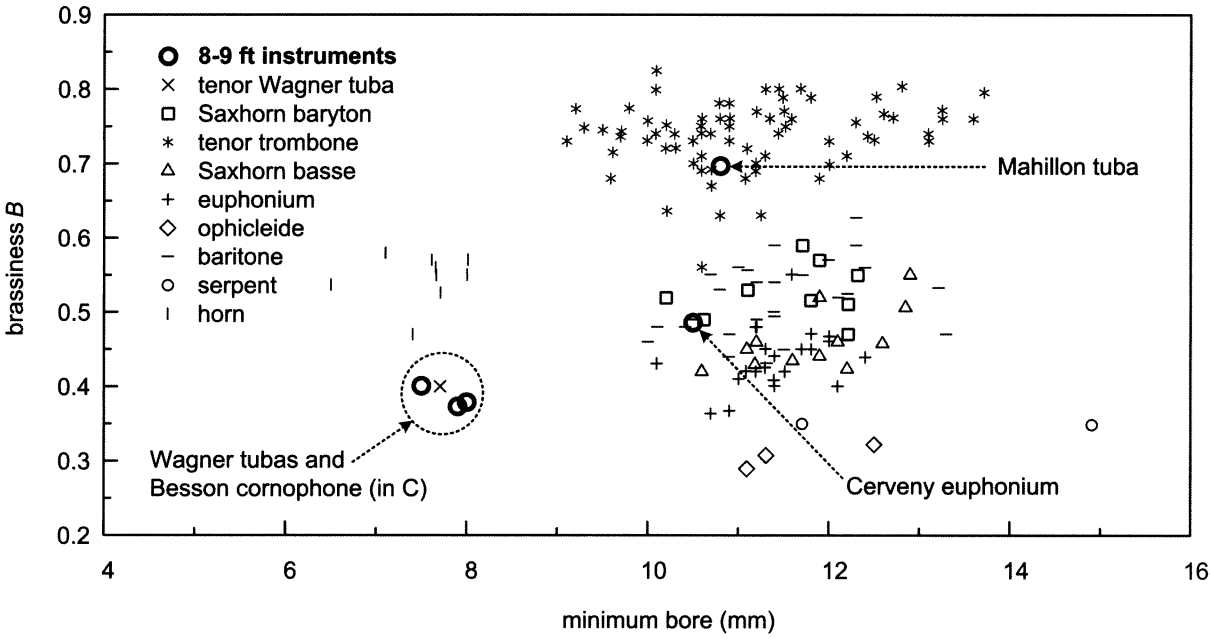

Figure 17. *Graph showing the classification of 8-9 ft brass instruments based on the Brassiness Potential parameter B [courtesy of Arnold Myers and Robert Pyle]. New data from instruments measured in this article are shown as black circles.*

Brassiness Potential parameter. The cornophone in E-flat however (Table 3), can not easily be compared to the Wagner tubas as it receives a mouthpiece with a wider shank, but in terms of parameter B, it is perhaps more similar to the family of bass tubas or bombardons.

In order to put these measurements in context, it is useful to consider a much wider data set including many more different types of instrument. The graphs in Figures 17 and 18 show values of the Brassiness Potential parameter B, plotted against the minimum bore for a large number of instruments with nominal pitch 8–9-ft (Figure 17) and 11–14-ft (Figure 18). For each category of instrument, only those considered to be representative of their type have been included. Added to these graphs are the data for Wagner tubas and related instruments from Tables 3 and 4. The new data points are shown as black circles.

Again it is clear that the group of Wagner tuba plots appear distinct from those of the other types of brass instrument; in terms of parameter B, their values are not dissimilar to some of the saxhorn type instruments, but the narrower minimum bore due to the use of a horn mouthpiece has significant acoustical implications, ensuring that their timbre is noticeably different.

CONCLUSIONS

Conceived in the era of industrialisation that was characterised by a tremendous number of new ideas for brass instruments, it is remarkable that the Wagner tuba has survived to this day. Acoustical tests and physical measurements have confirmed that the Wagner tuba has distinctive playing characteristics; these were found to be distinguishable from those of other modern brass instruments such as the horn, trombone and euphonium.

The Mahillon tuba is anomalous in that it is often referred to as a 'Wagner tuba', yet it is played with a trombone-like mouthpiece, has a bore profile close to that of the trombone, and behaves acoustically in a very similar way to a trombone.

The unpopularity of the Wagner tuba among some musicians is often associated with its perceived erratic tuning. Acoustical tests based on the resonances of the instrument air column did not show particular problems in this area, but there was considerable variation among the different models, with more recent instruments tending to perform better overall.

Interestingly, the modern double Wagner tuba, which has come under some criticism for lacking the individuality in sound of the separate single models in B-flat and F, showed the greatest variation in brassy timbre between the two 'sides' of the instrument. It is likely that this model is intended to be played in the same way as a double horn, utilising both the F and B-flat sides when playing. Nevertheless, the potential for tonal contrast on the

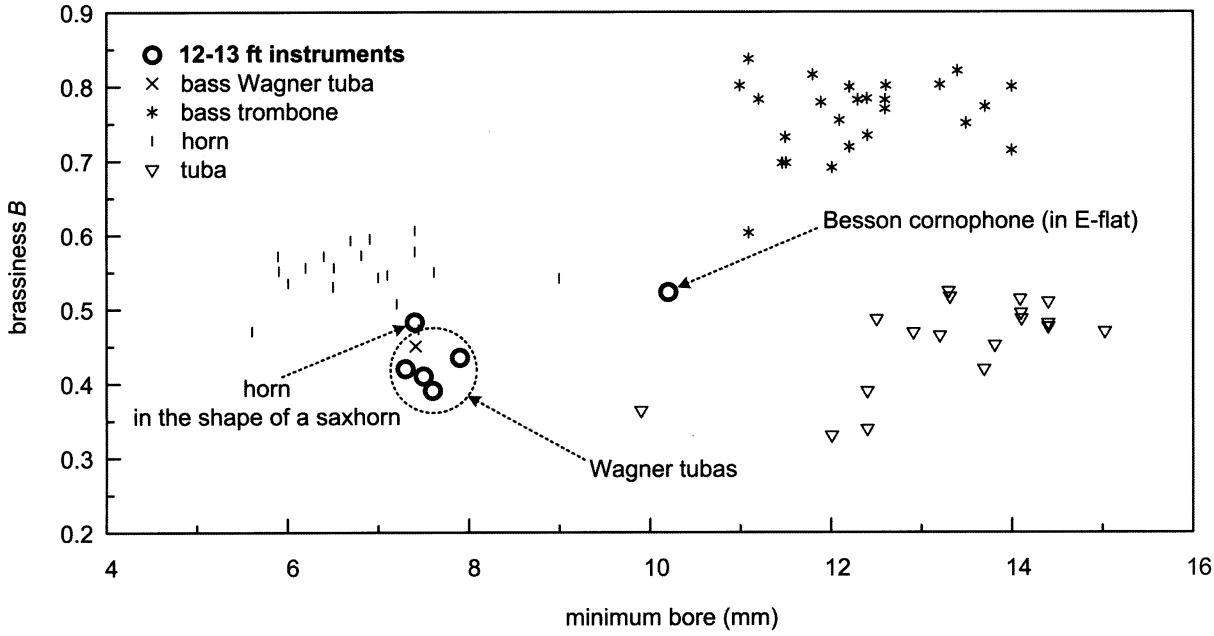

Figure 18. *Graph showing the classification of 11-14 ft brass instruments based on the Brassiness Potential parameter B [courtesy of Arnold Myers and Robert Pyle]. New data from instruments measured in this article are shown as black circles.*

particular instrument examined (GL (1) Alexander double) is great.

Arguably, the Wagner tuba has survived the test of time, albeit with varying popularity over the years, because of its distinct playing quality and timbre, shared only with the cornophone. The reason for the latter instrument's lack of success is possibly that its creation came slightly too late; there was no real desire for yet another similar instrument at the beginning of the twentieth century.

ACKNOWLEDGEMENTS

The authors would like to thank Géry Dumoulin, curator of the Brussels Musical Instrument Museum, for allowing access to measure the instruments included in this article, and also for his aid and assistance. Thanks also to Graeme Lee and John Sharp for kindly lending their Wagner tubas to be measured and examined. Also, we are very grateful to Shona Logie for help with processing acoustical data.

See overleaf for appendix of instruments with comparable bore profiles.

APPENDIX

Eighteen brass instruments, predominantly those with similar bore profiles to a Wagner tuba, were chosen for the measurements and experiments. A Vienna horn and trombone have been included in the data set for comparison:

EUCHMI (1677)	Wagner tuba in 12-ft F (R. Schopper, Leipzig, c.1925)
EUCHMI (2515)	Wagner tuba in 9-ft B-flat (Alexander, Mainz, early 1930s)
EUCHMI (2516)	Wagner tuba in 12-ft F (Alexander, Mainz, early 1930s)
EUCHMI (2854)	Wagner tuba in 9-ft B-flat (Alexander, Mainz, early 1930s)
EUCHMI (2855)	Wagner tuba in 12-ft F (Alexander, Mainz, early 1930s)
EUCHMI (5892)	Wagner tuba in 12-ft F (Moritz, Berlin, 1912-1955)
JS (1)	Wagner tuba in 12-ft F (Alexander, Mainz, 1980)
GL (1)	double Wagner tuba in 9-ft B-flat/12-ft F (Alexander, Mainz, 1980)
EUCHMI (5833)	tuba in 12-ft F (Mahillon, Brussels, c.1900)
MIM (R.13)	tuba in 9-ft B-flat (Mahillon, Brussels)
EUCHMI (3758)	cornophone in 8-ft C (F. Besson, Paris, c.1890)
EUCHMI (4208)	cornophone in 13-ft E-flat (F. Besson, Paris, c.1892-3)
EUCHMI (4509)	cornophone in 8-ft C (F. Besson, Paris, soon after 1905)
EUCHMI (3412)	euphonium in 9-ft B-flat (Červený, Königgrätz, 1891-1901)
MIM (JT205)	euphonium in 9-ft B-flat (Červený)
EUCHMI (4593)	horn in shape of saxhorn in 13-ft E-flat (probably France, late 18th/early 19thC)
EUCHMI (4461)	Vienna horn in 12-ft F (Fuchs, Vienna, late 19thC)
EUCHMI (3753)	tenor trombone in 9-ft B-flat (Mitsching-Alschausky, W. –Elberfeld, mid 20thC)

Explanation of acronyms:

EUCHMI	Edinburgh University Collection of Historic Musical Instruments
JS	John Sharp
GL	Graeme Lee
MIM	Musée des Instruments de Musique (Musical Instrument Museum in Brussels)