



Solo Duck Mooring Forces

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Solo Duck Mooring Forces

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Chapter 1

Introduction

One of the major difficulties in the design of a wave energy device is the occasional occurrence of severe conditions at sea. The largest waves far exceed typical amplitudes over the year. Although it would be possible to make devices large enough to capture the power efficiently in these conditions, it is almost certainly not economical to do so. Survival of the device in these conditions is, however, essential.

The difficulties in designing wave power devices for survival were identified by Salter in [1]. There are essentially two choices; give the device enough freedom to move with a large wave thereby limiting the force on the device or limit the possible movement while sustaining large forces. Either alternative means that at least an order of magnitude greater force or movement must be accommodated in the design just for survival. An approach that lies somewhere in between these two extremes is also possible. The best approach to take depends on type of device, its configuration and the power take-off scheme used. For the string of spine ducks the preferred approach has been to accommodate all the movement needed with low forces but this is not necessarily the best approach to take for a solo version. The spine ducks accommodate large movements with small bending angles in the spine joints. In the solo duck, on the other hand, the large movements would have to be accommodated in power take-off tension legs between the duck and sea bed. It is difficult to make hydraulic rams long enough to achieve this.

The work for this report was intended to repeat part of the work carried out in the narrow wave tank for the fourth year report [3, 4] but with force measurements made on a fixed solo version of the duck in a wide wave tank. The work has been extended due to the discovery of the phenomenon of snatching in tension legs.

If the downward force due to ^{α} wave on a device exceeds the upward calm-water buoyancy force that keeps the moorings under tension then the moorings will go slack. While the moorings are slack, the wave force can reverse and add to buoyancy to cause a very large snatching force when the mooring tension is suddenly restored. The snatch force far exceeds even the large forces that a device with limited movement would normally expect to sustain. When tension is restored, the stiffness of the moorings combines with the mass and added mass of the device to produce an oscillation in this force. The oscillation decays over several cycles. The effect can be seen in figure 3.3. The magnitude of the snatch force depends on the stiffness of the moorings and on the kinetic energy built up in the device just before snatching occurs. The phenomenon is not limited to stormy conditions, it occurs regularly in moderate seas.

The effect of snatching presents a designer with a further choice in the design of a tension leg with limited movement. Either design the leg to take compression forces as well as tension or else allow for the leg to go slack but include a method for soaking up the large energy when tension is restored. A

brute-force approach in which the leg is designed to take the full snatch forces would almost certainly be impractical. The requirements for the design are further complicated by the fact that the device would have to survive the effects of the down force even when expected failures in the components occur over its operating life.

The content of this document is intended to give a designer the information needed to design a limited-movement tension-leg mooring system for the solo duck. The methods used in this report would also be applicable in other tension leg applications.

1.1 Summary of test conditions

- The standard test case was a model of a solo duck with the same dimensions as that in [6, 7, 8], fixed in heave and surge but free to move in pitch. The mooring arrangement is kept under tension by buoyancy in the duck. The forces at the anchor points were measured. Tests varying duck width, shape corner roundness, submergence and mooring compliance were also included.
- The models were tested in Pierson Moskowitz spectra with varying amplitudes and periods. They were also tested in freak waves with a period in the centre of the useful range but with varying amplitudes and phases.

1.2 Main conclusions

- The effects of downward wave forces exceeding upward buoyancy forces in a limited movement tension leg application are potentially devastating. Tension leg devices in which this may occur should be designed to survive these effects. The effects are likely to occur in cases where the bulk of a device body is either at or close to the water surface or in more submerged cases in which the buoyancy force is low enough.
- Despite a move to the wide tank the force measurements (apart from snatch forces) match those measured in the narrow tank for the fourth year report.
- Duck capsize contributes to the downward force which causes the tension legs to go slack and thereby also contributes to the snatching phenomenon.

Chapter 2

Test conditions

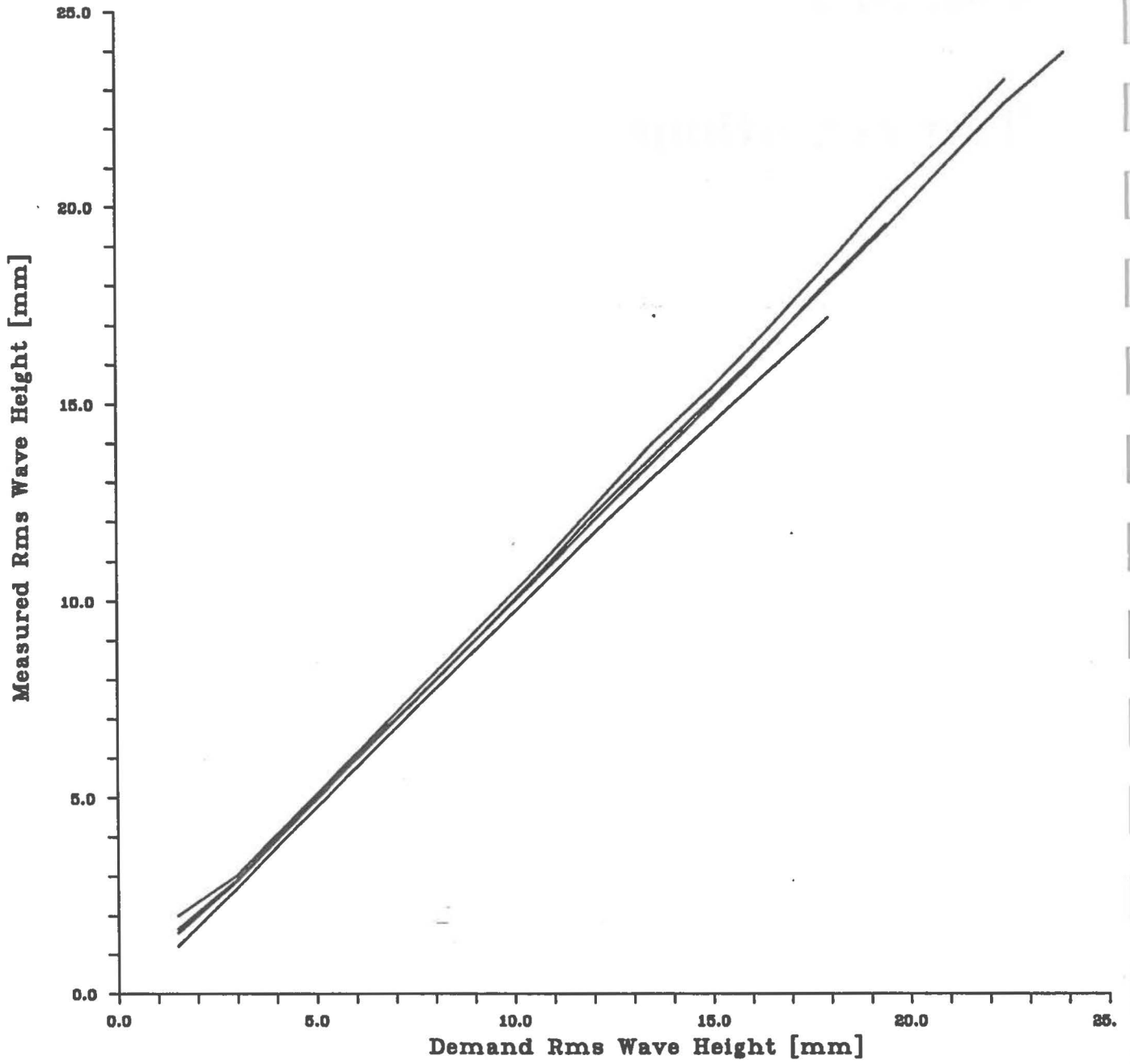


Figure 2.1: Measured Pierson-Moskowitz rms wave height

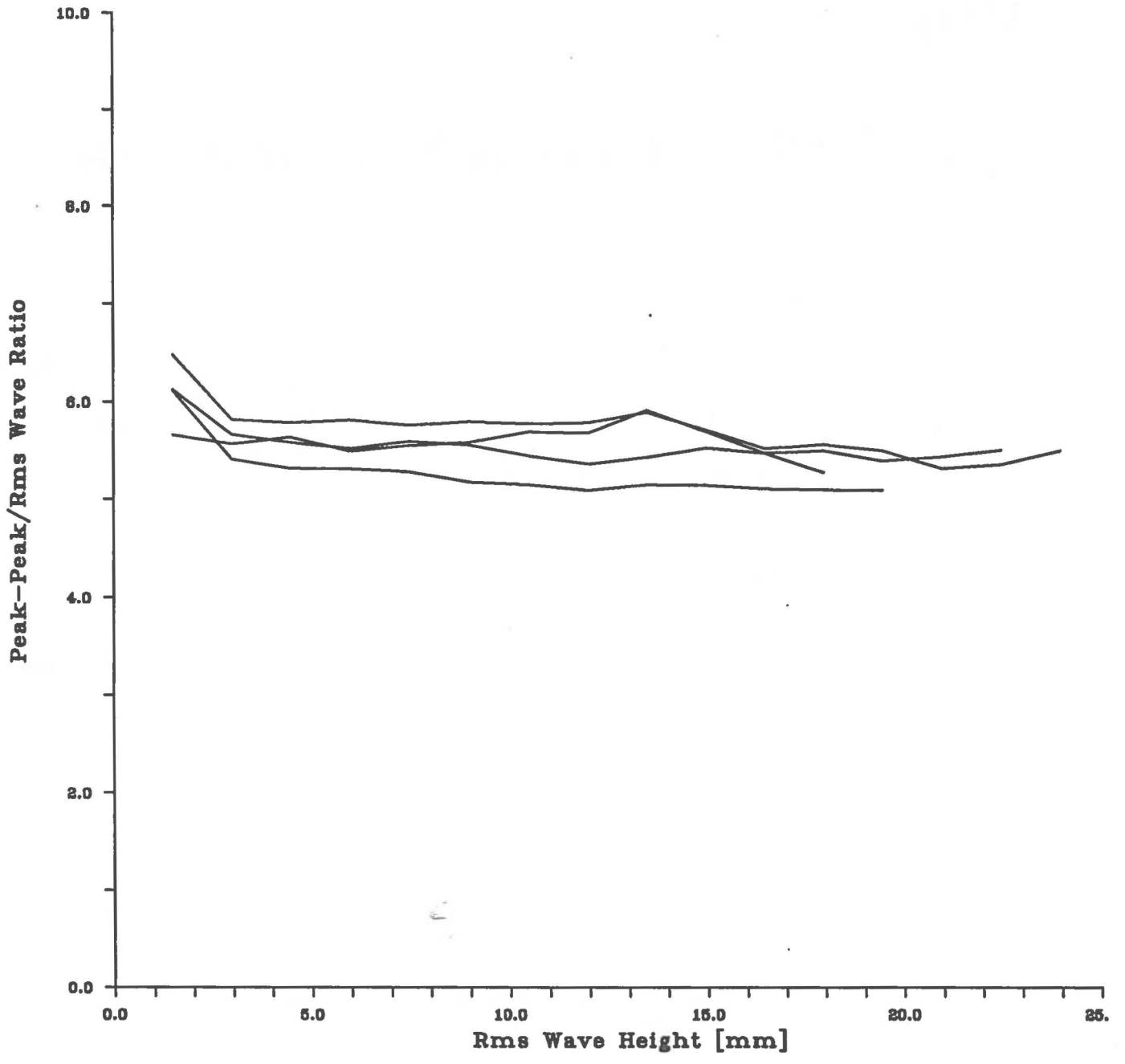


Figure 2.2: Measured Pierson-Moskowitz peak-peak/rms wave height ratio

Chapter 3

Solo Duck in Pierson-Moskowitz waves

The most critical aspect in the design of the solo duck for limited movement is the resulting high force that is incurred. Forces in the solo duck are especially critical due to the phenomenon of snatching when using tension legs for power take-off. It is essential that, for survival, the duck is designed to sustain the maximum forces that would be expected even in extreme conditions. This chapter investigates forces in the wide range of frequently occurring wave conditions with varying periods and amplitudes. In particular it explores the reasons for snatching and the effect it has on these forces. Forces in extreme waves are presented in chapter 4.

3.1 The snatching effect

The snatching effect can clearly be seen by looking at force records in which it appears. It is worse in the the fore tension wire than in aft and it also appears to be more severe in the center of the useful frequency range. A worst case example will be presented to illustrate the effect.

3.1.1 Fore force records

Figure 3.1 shows a series of force records measured on the fore tension wire of a solo duck in Pierson-Moskowitz wave spectra. The wave amplitude is increased in steps of one quarter of the standard normal steepness so that the bottom trace represents two times the PM norm. The energy period of the wave is 0.94 seconds. It is the second of the four standard test periods that were used for all the PM tests (see section () for full details). The records show the forces due to the waves super-imposed on the static tension due to buoyancy.

In the fourth record, representing standard steepness, the wave force at thirteen seconds into the trace has reduced the total force to the point where the wire nearly goes slack. In the next record the wire has gone slack and the force immediately following rises sharply and the trace is smeared for a short time after. This force is due to snatching when the tension is suddenly restored. The smear is a high frequency oscillation due to the spring in the mooring line combined with the mass and added mass of the duck. As the amplitude increases further, the resulting peak rises quickly to several times the surrounding peaks and further occurrences of snatching appear in the trace. It can be seen that in all of these the wire has gone slack just prior to snatching.

The records also occasionally show a sudden drop in force from one wave amplitude to the next. Examples of this can be seen in the third trace at 14 seconds, in the fourth trace at 13 seconds and

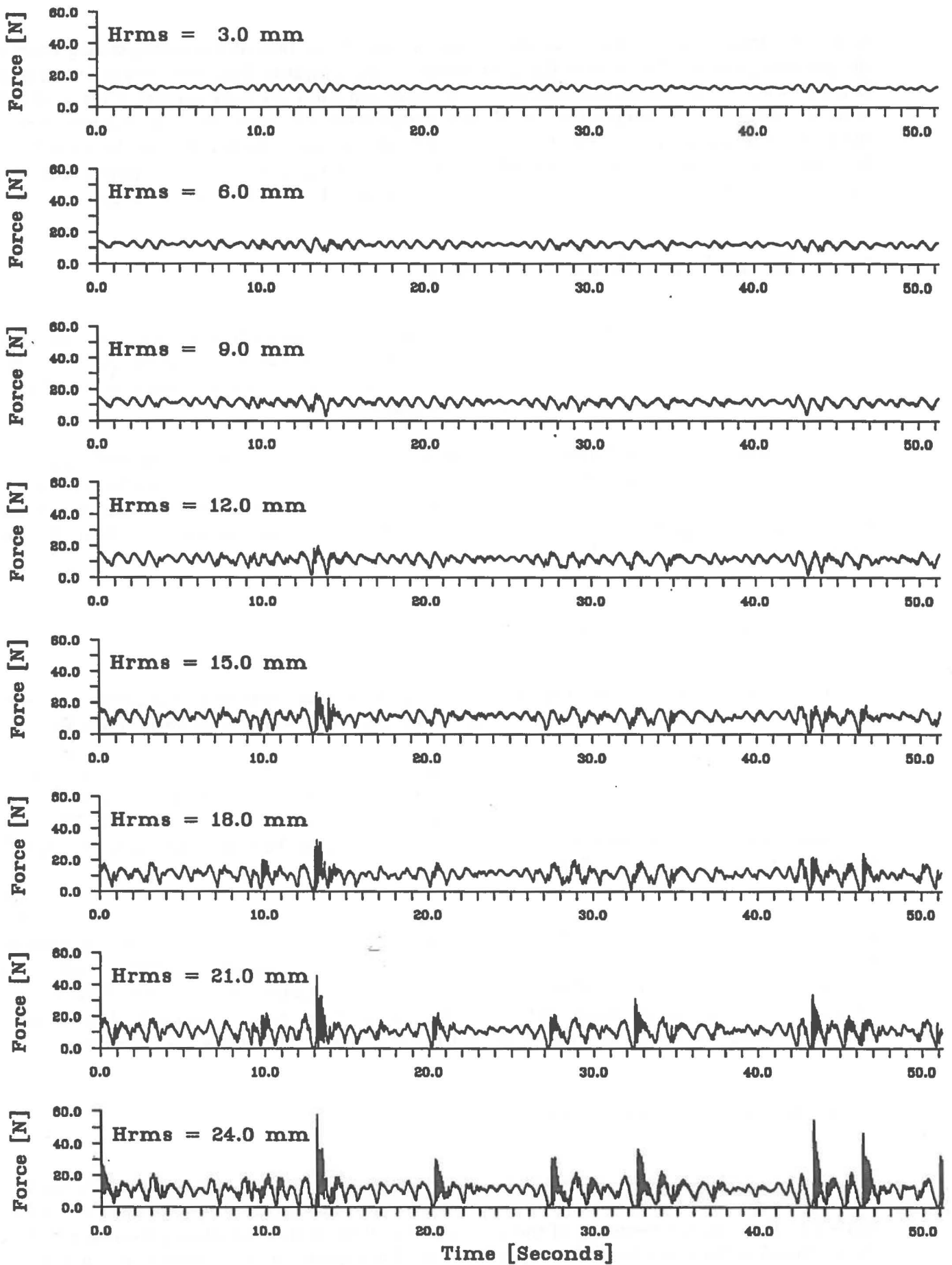


Figure 3.1: Fore force records varying Pierson-Moskowitz wave height

in the fifth trace at 46 seconds. The force is significantly lower than at the corresponding times in the preceding traces. The cause of this phenomenon is duck capsizing. Since the duck is free to move in pitch, a wave crest will lift the beak up but it will return when the wave has passed if the amplitude is small enough. At a certain critical amplitude a wave crest will cause the duck to capsize beyond the point where it quickly recovers. This leaves the beak with all its ballast clear of the water in the following trough. The weight of the beak is now adding to the down force. It appears that duck capsizing contributes to the cause of the wires going slack and therefore also to snatching.

3.1.2 Comparison with aft force records

The corresponding aft forces for the same wave conditions are shown in figure 3.2. The downward forces are not as high as in the fore line so that the snatching peaks do not rise as sharply. There are, however, oscillations in the force and they occur at the same time as the snatching events in the fore wire. These oscillations are induced by the fore oscillations.

High peaks and resulting oscillations may also occur if most of the down force is applied on one side of the duck, thereby causing one of the mooring lines in either fore or aft to go slack. The force in the other line would reduce but the wire would remain in tension. Since the same load-cell is used for both wires (see figure ()), the record would show a typical snatching event but without the trace touching the zero line prior to the snatching peak.

3.1.3 A closer look at snatching

Expanding the time scale on the graph gives a clear picture of the snatching oscillations. Figure 3.3 shows a 6.4 second section of the fore force records in figure 3.1 starting at 42 seconds into the run.

In the fourth record the force at 43.2 seconds comes very close to zero and a small oscillation follows. In the next record the trace touches the zero line and the oscillation peak rises sharply. Increasing the amplitude further causes the snatch peak to rise far above the normal surrounding peaks. The traces also clearly show the slow decay in the oscillation. This is due to the small added damping that the water provides at the oscillation frequency.

Note that the snatch forces do not always rise immediately when tension is restored. There is often an initial slow rise or small peak. This is most likely due to asymmetry in the forces that cause the wires to go slack. When the pair of the wires in either fore or aft go slack it is unlikely that tension will then be restored in both of them at the same time. Asymmetry will cause one of the wires to snatch first. The full kinetic energy in the motion of the duck can only be absorbed when tension in both of the wires is restored. It is only then that the very large snatch forces are produced.

3.1.4 Fourier transform of force records

The high oscillation frequency of snatching suggests that it should appear in a Fourier transform of the force record. This is indeed the case. Figure 3.4 shows the spectrum of the fore force record from figure 3.1. The sampling frequency of the force record is 40Hz so that the aliasing frequency is 20Hz. This is therefore the upper limit of the spectrum. The force spectrum that is directly due to the wave spectrum can clearly be seen at all amplitudes at around 1Hz.

In the first trace, apart from the main force spectrum, there is a small contribution at around 15Hz. It can hardly be seen but grows larger and wider in subsequent traces as the wave amplitude is increased.

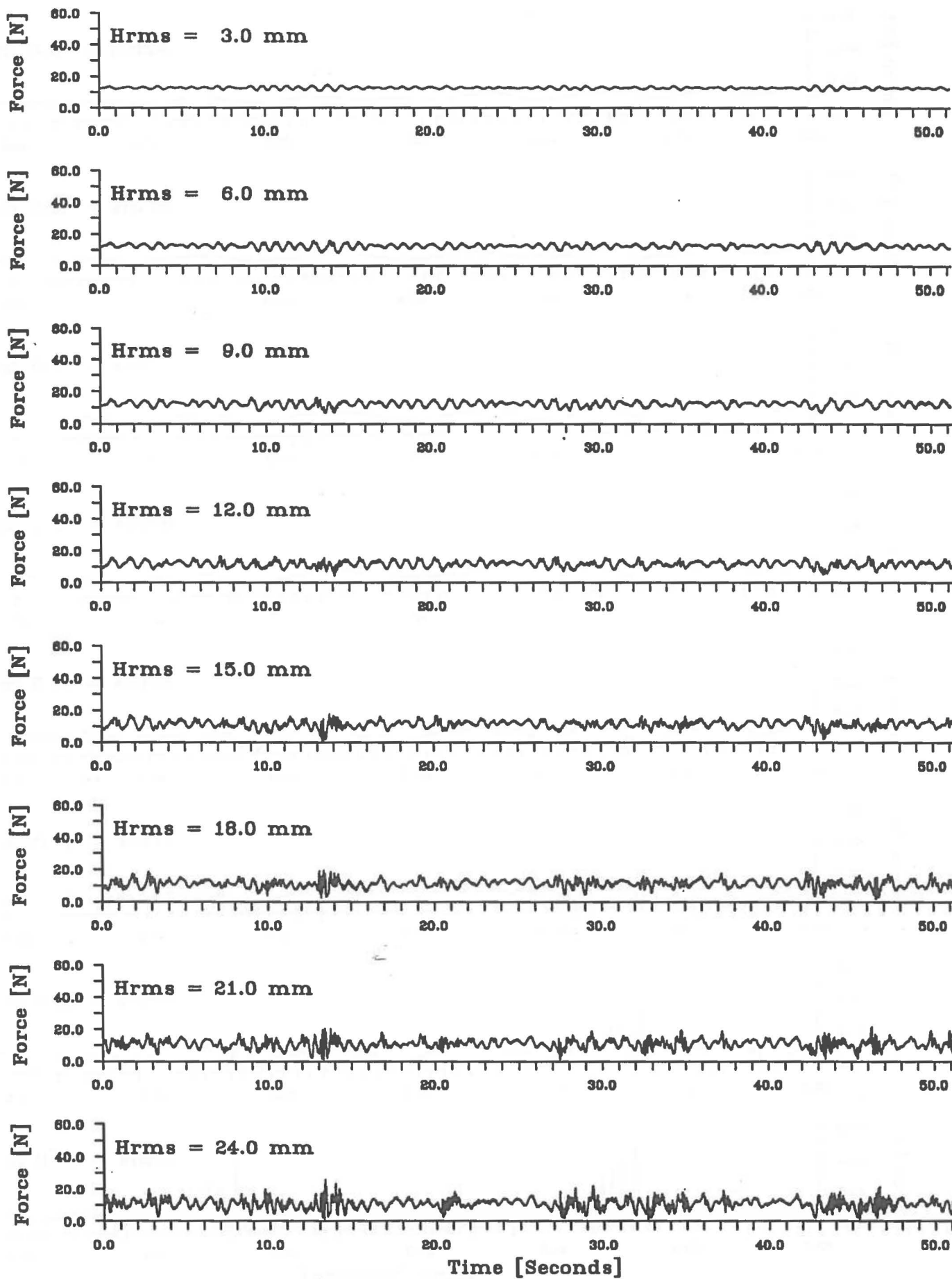


Figure 3.2: Aft force records varying Pierson-Moskowitz wave height

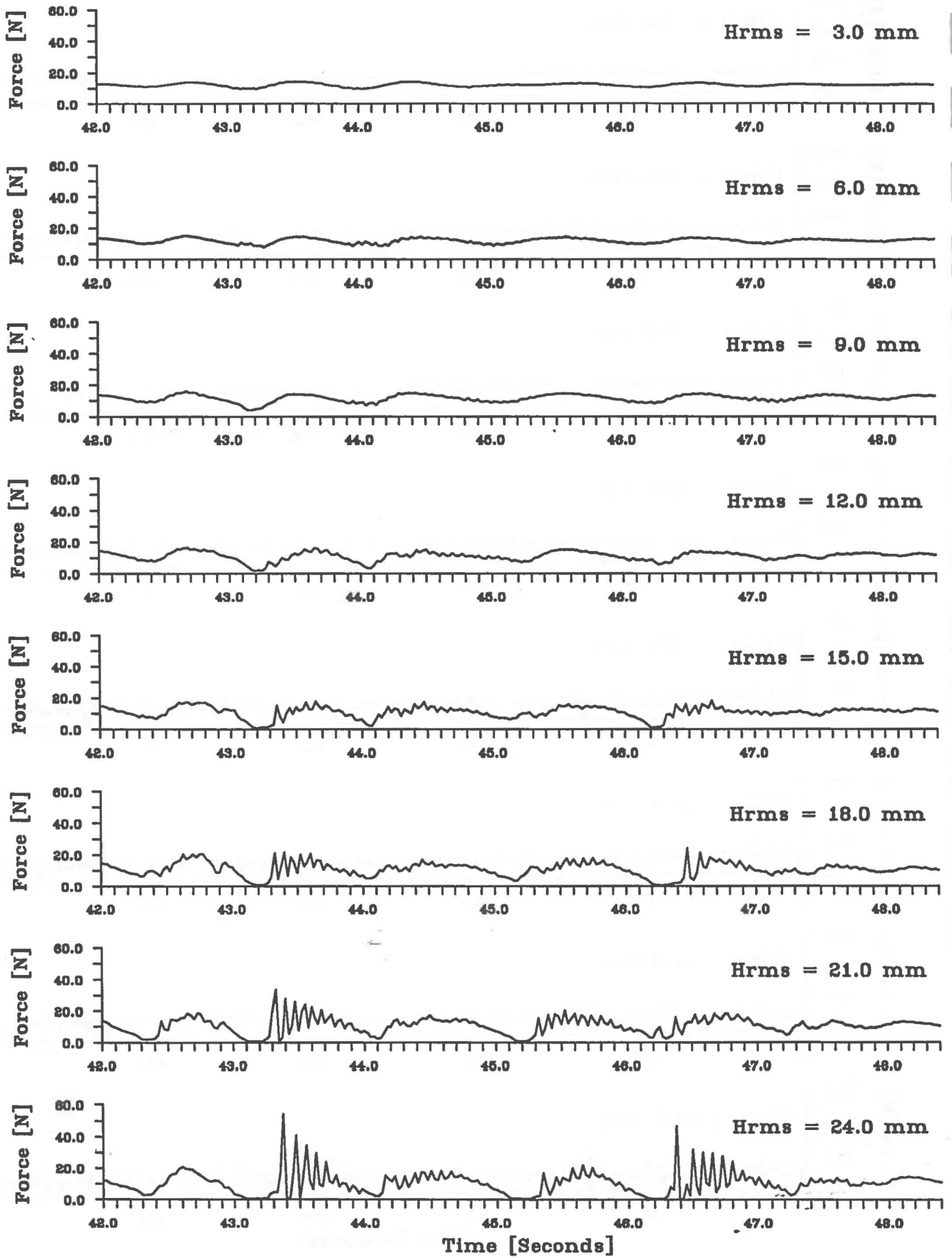


Figure 3.3: Time-expanded force records varying Pierson-Moskowitz wave height

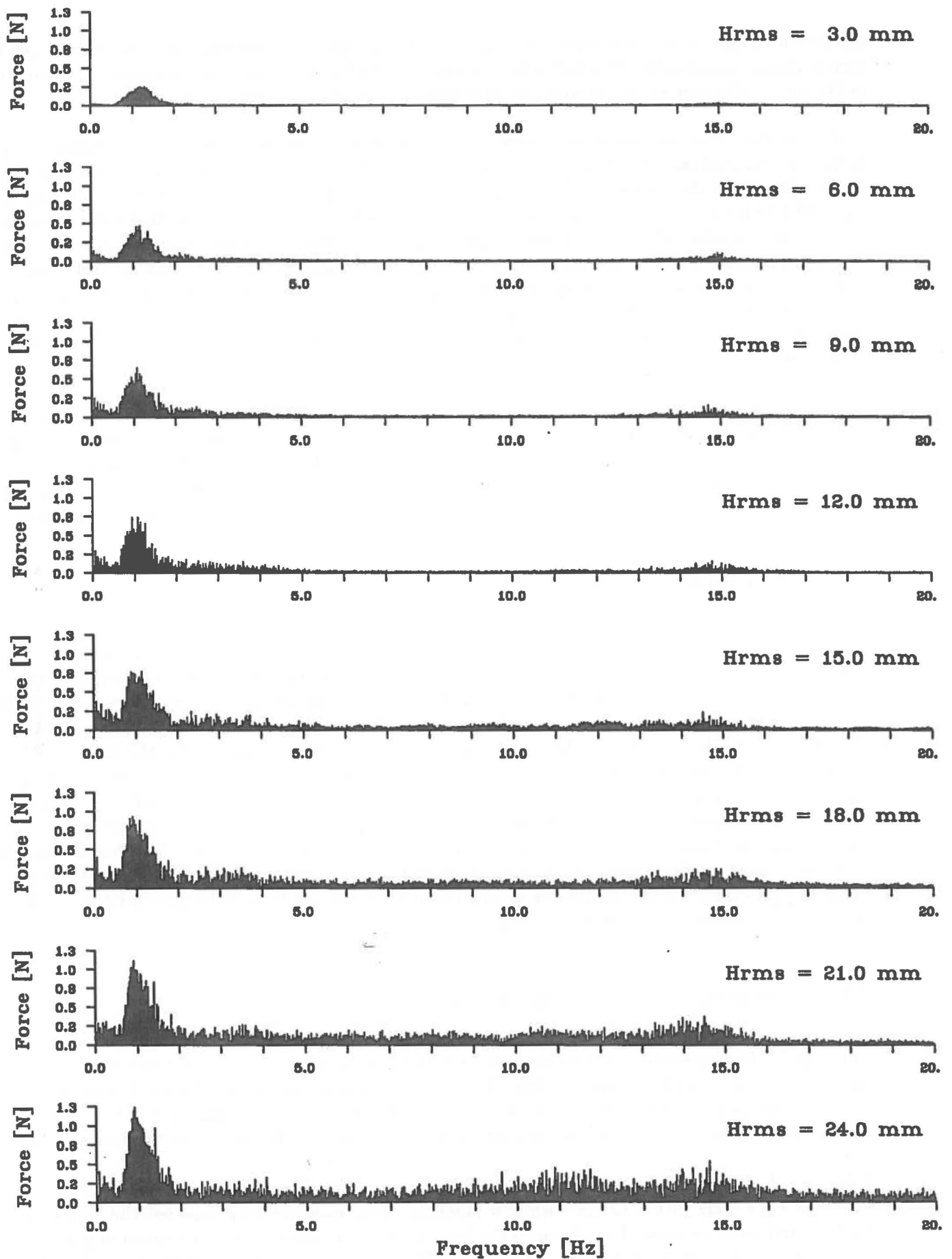


Figure 3.4: Fourier-transformed fore force records varying Pierson-Moskowitz wave height

1

By the last trace there is a contribution right across the spectrum but the main oscillations can be seen between 10 and 15Hz. The rest is more likely to be background noise due to sharp discontinuities in the signal, clipping when the wire has gone slack and wave slamming on the duck.

It is interesting that the oscillations cover such a wide band. It implies that there is no single natural frequency. An explanation for this is that the mass and added mass in fore and aft are very dependent on the attitude of the duck in pitch. The greatest combined mass in fore is achieved when the duck is capsized and the ballast in the beak is in line with the mooring wire but pointing diagonally away from it. This has the effect of decreasing the natural frequency at high amplitudes when capsize and snatch events often coincide. The contribution at 15Hz at low amplitudes is due to the natural frequency of the duck in its normal operating attitude. It is not necessary for oscillations at this frequency to be induced by snatching. There are many non-linear effects in the system (e.g. stiction in the pitch bearing) that would induce small oscillations in the lines. The very large ones are, however, due to snatching.

The figure also shows a significant contribution at frequencies that are well below the lower limit of the wave spectrum (about 0.5Hz). The infrequent occurrences of non-linear behaviour in pitch adding to the down force are responsible. In particular, the occurrences of slow recovery from capsize contribute most of it at increased amplitudes. There is also a net total down force that reduces the mean force to below the buoyancy force. The net down force increases as capsize events become more frequent.

3.1.5 Filtered force records

The separation in the frequency domain of the normal wave spectrum and the snatch spectrum means that it is possible to derive a force record that excludes the snatching events. This is shown in figure 3.5. The fore force records from figure 3.1 have been filtered to exclude frequencies above 2.5Hz (2.0Hz is the upper limit for wave generation). The traces in the two figures now look identical apart from the smear caused by snatching. The result is a wave record that represents what the forces would be without the effect of snatching. This would be useful for a design that avoids it (e.g. by designing the legs to support compression as well as tension). The method is not completely accurate as clipping of the unfiltered signal at zero tension causes the the downward force to be underestimated while snatch forces cause the upward forces to be overestimated when the signal is filtered. The effect is not likely to be very large as the traces do not look set to go far below zero (see the expanded version of the trace in figure 3.3). In the remainder of this chapter all the results will be presented for both the filtered and unfiltered versions of the force measurements.

3.1.6 Low frequency contribution to down force

Filtering the force measurements to keep only the the frequency components that are below the lower limit of wave generation reveals the down force due to capsize (see section 3.1.1). Figure 3.6 shows the low frequency content of the measurements from figure 3.1. The straight line is the calm water tension due buoyancy. Note that all the traces show a reduction in this tension at all wave amplitudes.

Filtering all but the low frequency components of force is equivalent to averaging the force over more than one wave cycle with a suitable window function. Whenever the duck capsizes, the ballast in the beak contributes to a mean down force. If the beak is elevated only part way to capsize or if it recovers quickly from full capsize then a moving average will only show a small part of the down force. If, on the other hand, the duck is slow to recover from capsize then the moving average can show the full down force. In the absence of pitch angle measurements, the low frequency content of force on the mooring lines can give an idea of the frequency and duration of capsize events.

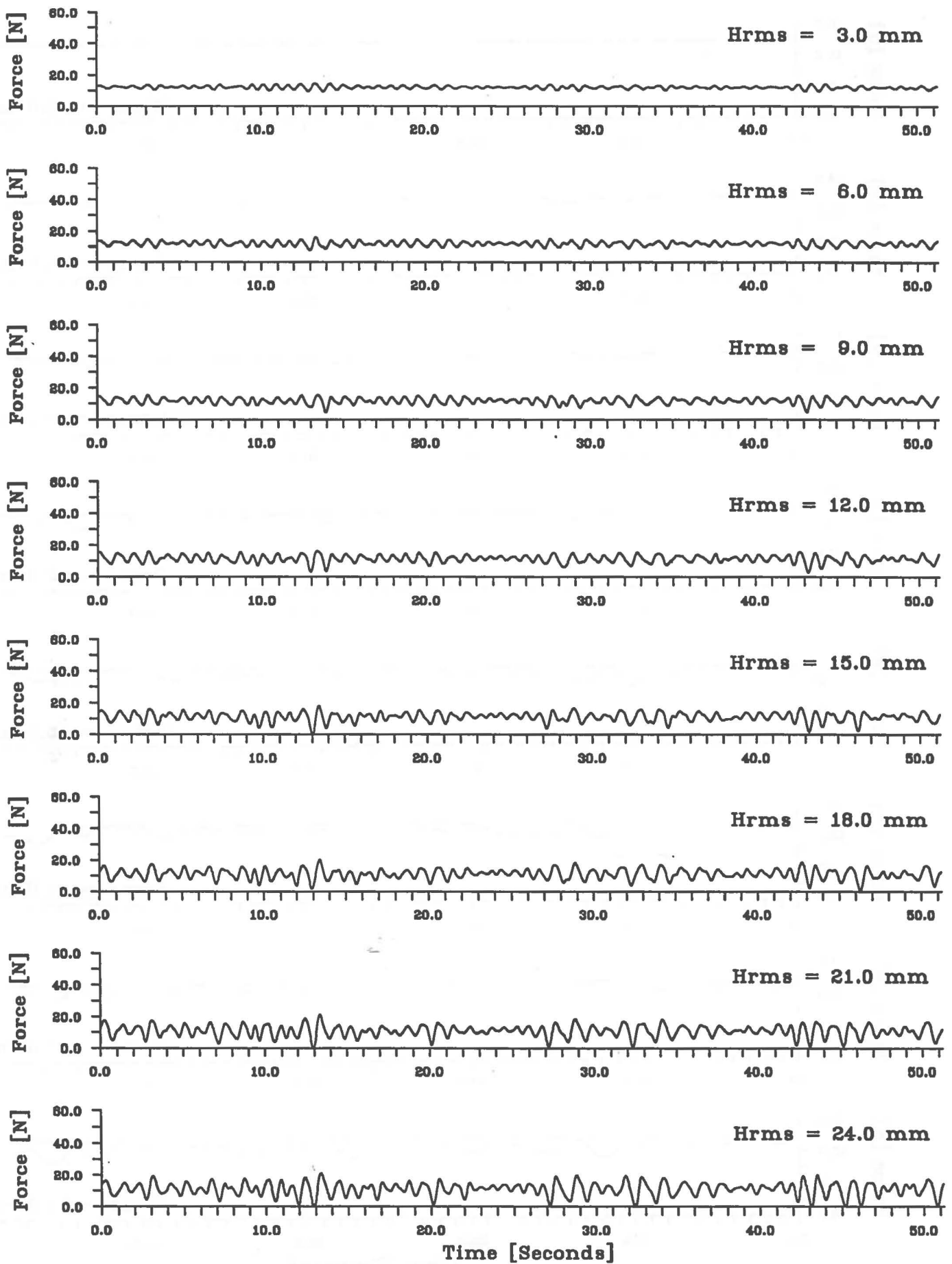


Figure 3.5: Filtered fore force records varying Pierson-Moskowitz wave height

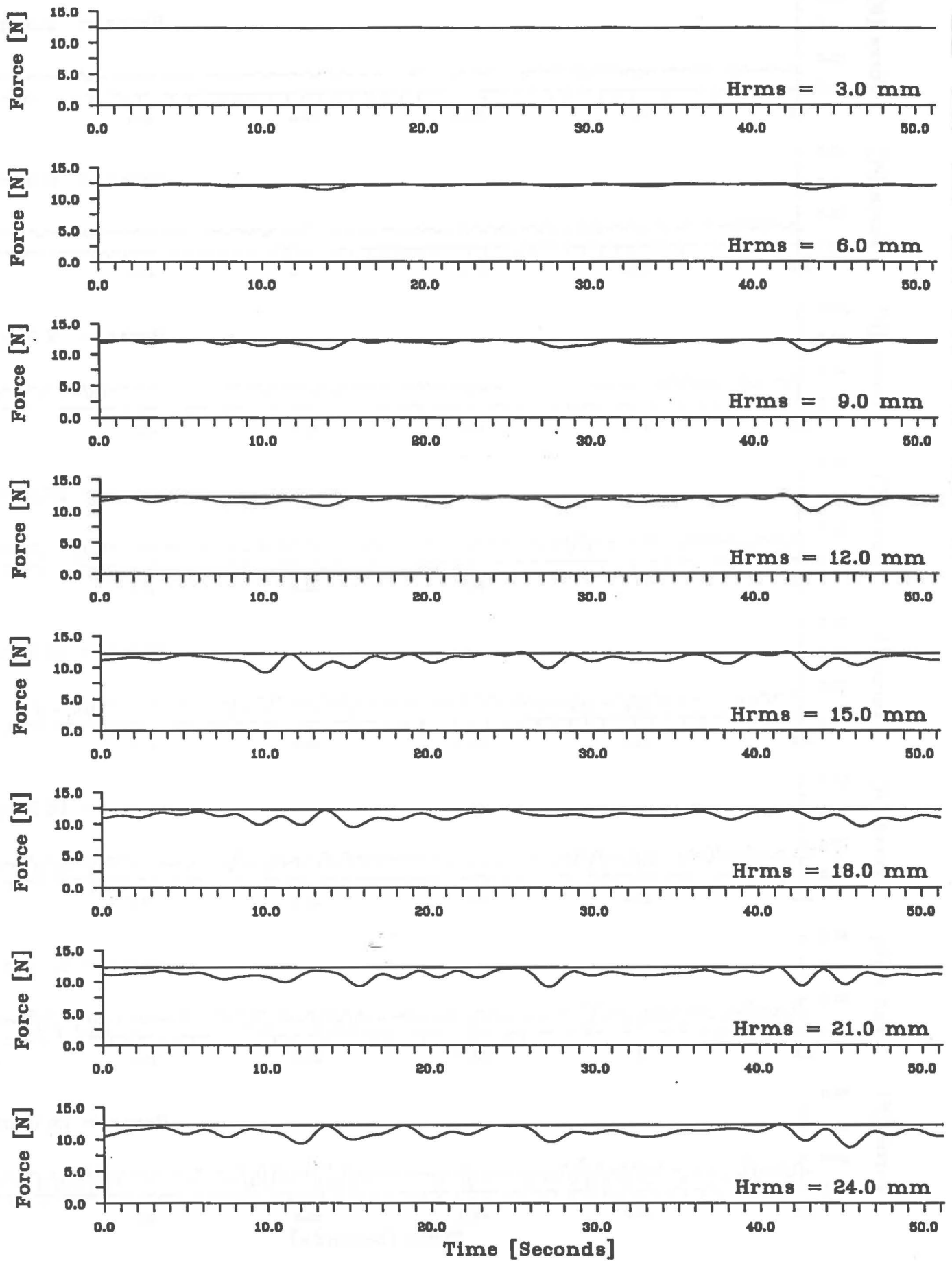


Figure 3.6: Low frequency contribution to force varying Pierson-Moskowitz wave height

Note that the traces show a great deal of sensitivity to the precise wave height. At certain critical amplitudes the duck will only just capsize and recover slowly while increasing the amplitude a little further can produce a more violent capsize from which the duck is thrown back to its normal attitude quickly. Increasing the amplitude still further can cause a return to slow capsize.

3.2 Force measurement results

The results from the force measurements are presented here but note that any snatch forces presented are very dependent on the compliance in the moorings (see chapter 6). For very stiff moorings it would be safe to assume that the kinetic energy absorbed in snatching does not depend on compliance. The forces can therefore be converted for a different mooring compliance by using the simple relation that the square of the ratio of snatch force is inversely proportional to the ratio of compliance.

See also chapters 7 and 8 for the effect of submerging the duck and the effect of varying the width and corner roundness of the duck respectively.

3.2.1 Rms and peak forces

Following the style of presentation in the fourth year report [3], figure 3.7 shows the rms and peak forces. The forces are presented for each of the four test periods (see section () for a full description of the test conditions). The trace in the unfiltered fore graph with the two high peaks is the one presented in figures 3.1 to 3.5. It is clearly the worst for snatching. The graphs show the forces in fore and aft but it is still useful to compare them with the heave and surge forces in [3] pages 2.52 to 2.65 (see chapter 5 for derived heave and surge forces in this report).

The graphs show a similar pattern to those in a narrow tank [3]. The peak forces are several times higher than the rms ones and both forces are largely independent of wave period. The most striking difference is the sudden sharp rise in the unfiltered fore peak forces above about 15mm rms wave height. These are, of course, the snatching force peaks. In the filtered version of the same records these sharp peaks disappear. The graph shows the more moderate peak forces that would result if snatching was avoided. Snatching peaks can also be seen in the aft peak forces although they are not much higher than in the filtered version.

Snatching apart, the peak forces in both fore and aft display a leveling-off trend. At high wave amplitudes the forces are prevented from rising much further. This is a welcome trend especially in a design that limits duck movement.

3.2.2 Minimum and maximum forces

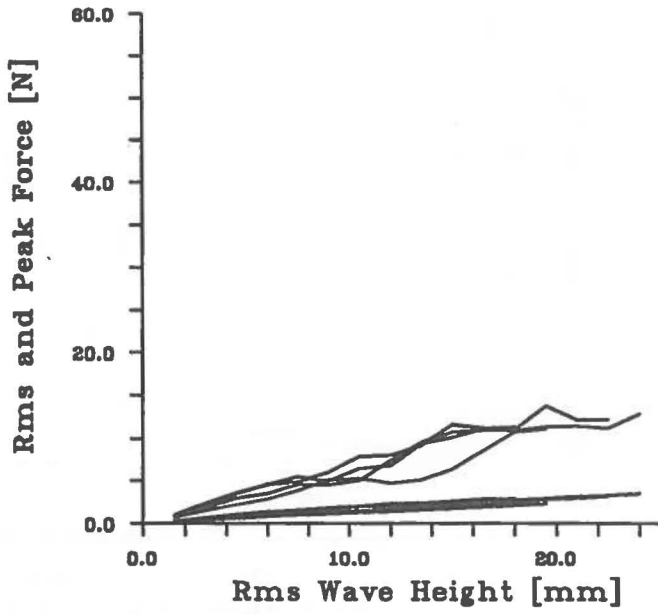
There is a great deal of asymmetry in the positive and negative peak forces. The negative peaks have the added effect of down force due to non-linearity and in particular capsize. They also include clipping when the lines have gone slack. The positive peaks, on the other hand, include snatching. This suggests that it would be useful to present these separately.

Figure 3.8 shows the minimum and maximum forces drawn on the same graphs. The buoyancy force is drawn as a straight line in the middle and is useful for highlighting the asymmetry. The minimum and maximum forces diverge from this line as the wave amplitude is increased. Compare these graphs with figure 3.7.

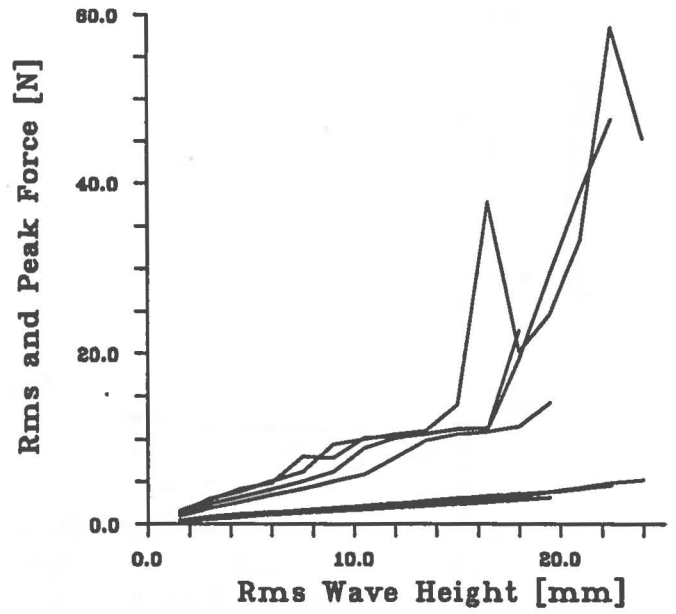
The rapid increase in the down force can now clearly be seen as a drop in the minimum force, especially in the unfiltered fore graph between 6 and 14mm rms wave height (depending on the wave period). The effect can be seen in all the graphs if each trace is followed individually. Compare these minimum forces with the corresponding forces in heave, section 5.1.2 and in [3] pages 2.59 to 2.65.

The maximum forces now show the snatch peaks more clearly. There is a smoother rise in these forces

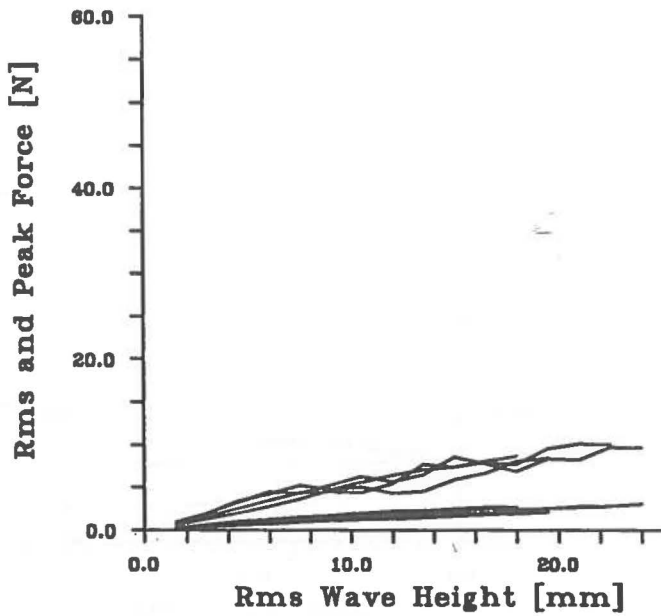
Unfiltered Aft



Unfiltered Fore



Filtered Aft



Filtered Fore

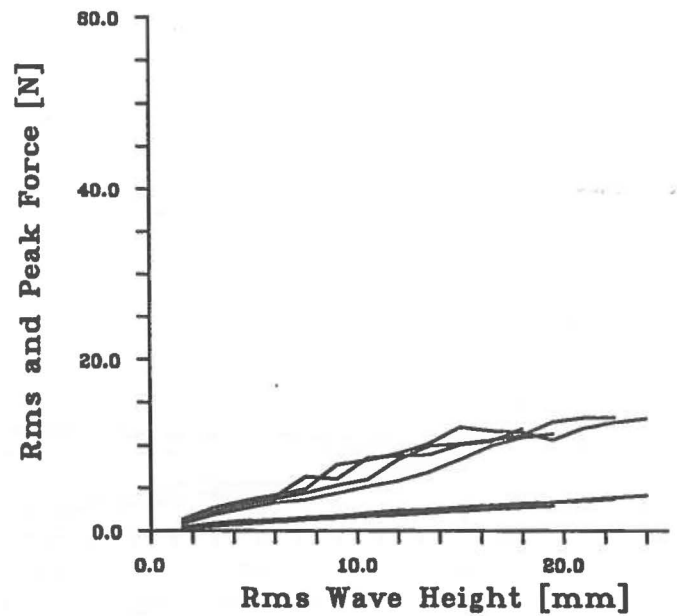


Figure 3.7: Rms and peak forces in Pierson-Moskowitz waves

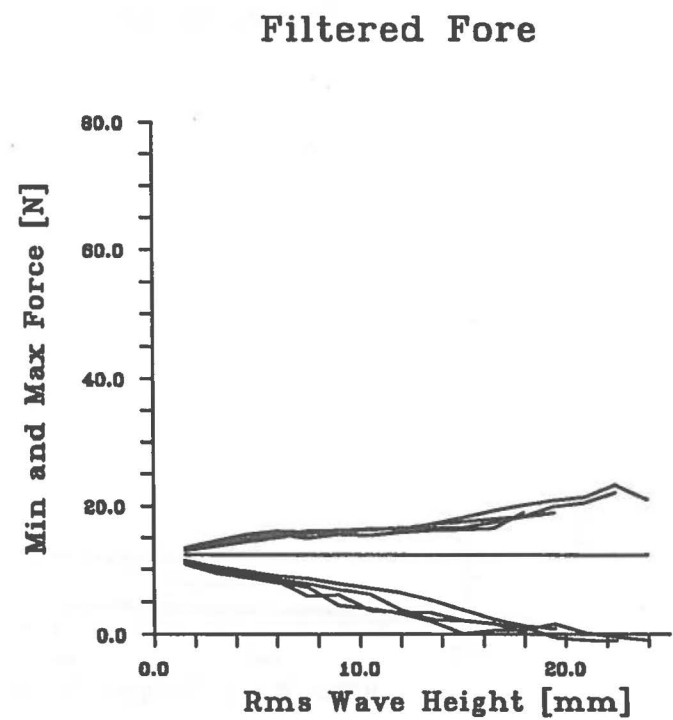
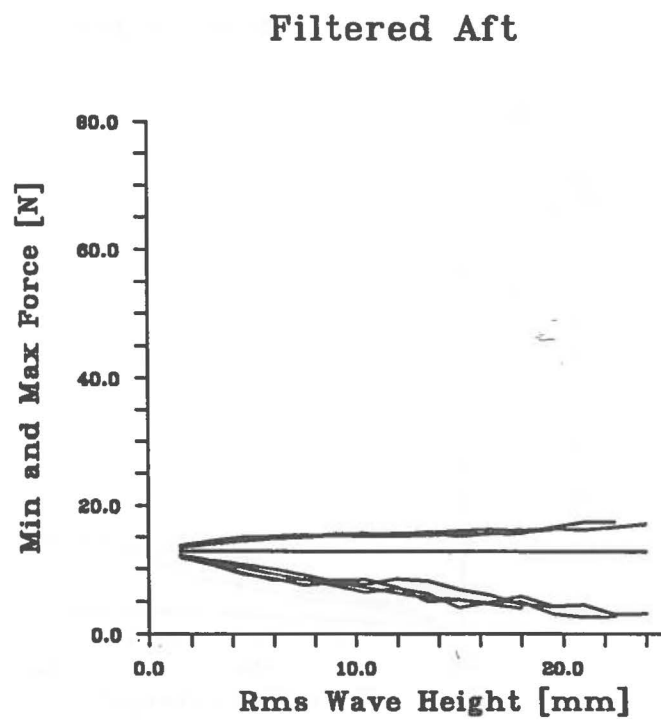
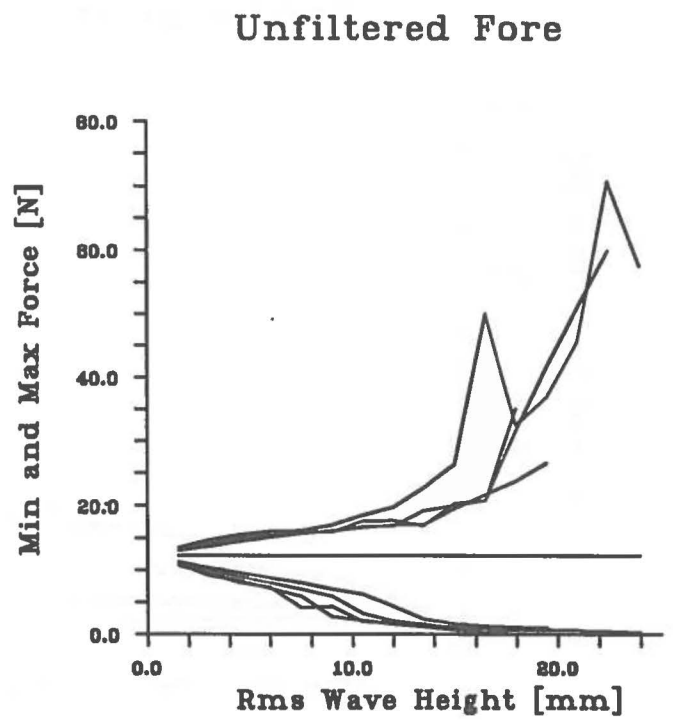
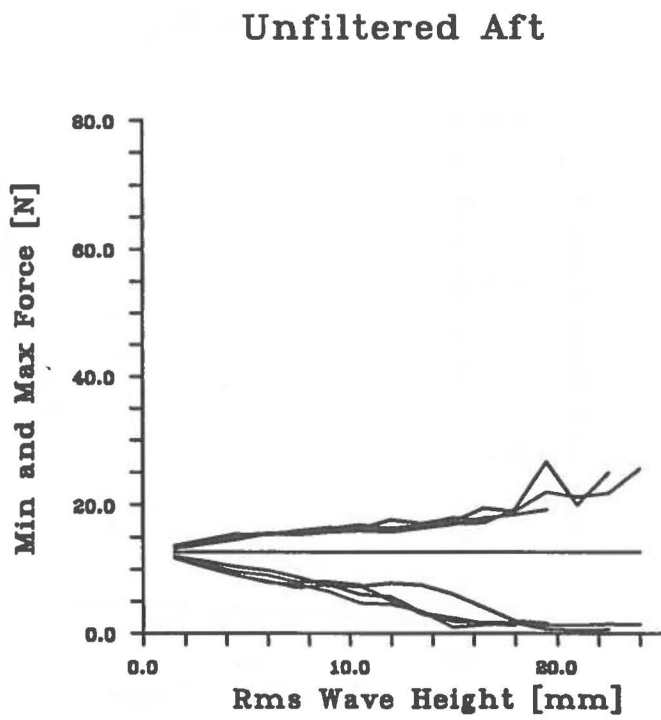


Figure 3.8: Minimum and maximum forces in Pierson-Moskowitz waves

up to the point where snatching occurs. In particular, with the effects of down force removed in aft, the snatch peaks can now be distinguished.

At rms wave amplitudes below about 6mm, the minimum and maximum forces are much more symmetric, the wave amplitude is small enough for linear behaviour even at the peaks. Both minimum and maximum forces display a leveling-off trend. This trend looks set to continue but for effects of down force and snatching.

Filtering does not remove the effect of down force so the leveling-off trend is not expected to resume in the minimum forces of the filtered records. They may be expected to resume in the maximum forces but this in fact does not happen. After leveling-off, the maximum forces start to rise again at about 14mm rms wave amplitude in fore and at about 18mm in aft. It is not clear whether this is a real effect or whether it is simply due to the snatching peaks causing an overestimate of the maximum forces when filtered. The rise in force in both fore and aft coincide with and appear to be proportional to the corresponding snatch peaks. This suggests that the latter is the cause.

3.2.3 Rms forces

The rms forces presented in figure 3.7 are dwarfed by the very large snatch peaks. A closer look with a more appropriate scale is needed. Figure 3.9 gives a more clear picture of these forces.

The rise in rms forces follows a similar pattern to the rise in peak forces (figure 3.7 but see also figure 3.8). There is a rapid rise at low wave amplitudes in both fore and aft up to about 5mm rms wave amplitude. It is followed in fore by a leveling-off but this does not last very far. The forces soon rise again but not as quickly as in the small waves. In aft there is a gradual decrease in the slope over the whole range. It is not surprising that the rms forces follow a similar trend to that of the peak forces. The definition of rms is such that it gives heavier weight to the peaks than to the rest of the signal. The effects of down force, clipping and snatching are therefore likely to make a significant contribution to the trend in the rms forces.

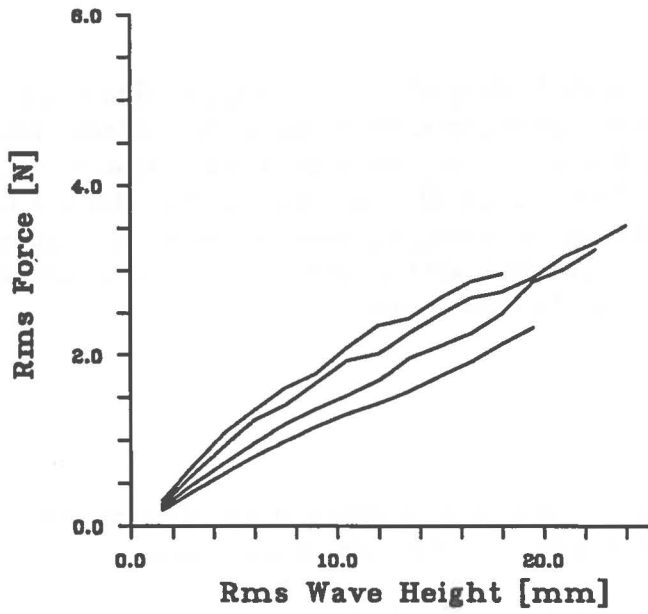
The graphs also show a definite trend with the different wave periods, especially in aft. The shorter waves give the higher forces. This is not surprising as for a given wave amplitude the water particles in the longer waves have a lower velocity and acceleration than in the corresponding shorter waves. The trend does, however, differ from that in the fourth year report [3]. The heave forces (pages 2.59 to 2.65) are almost completely independent of period while the surge forces (pages 2.52 to 2.58) if anything show a reversed trend. It is not clear why this is the case. In both cases however it can be seen that broadly speaking there is no significant dependence of the forces on the wave period.

3.2.4 Rms force coefficients

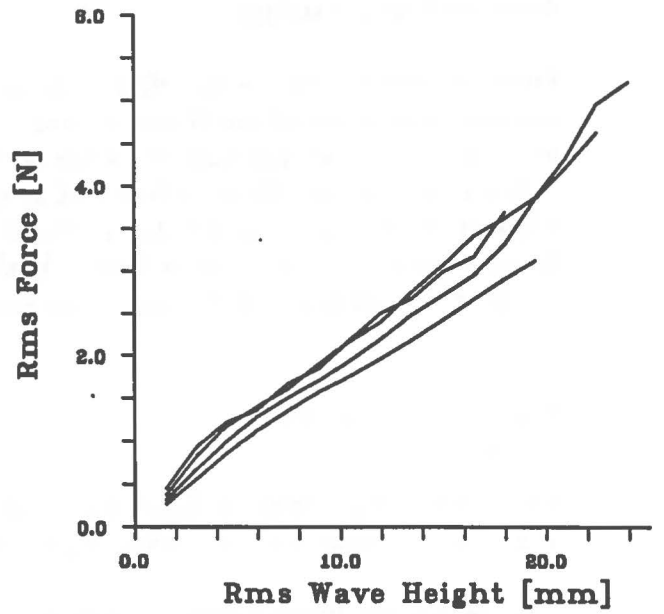
In the second year report [2] a force coefficient was developed especially to suit ducks. The coefficient was defined for monochromatic waves. It was later extended in the fourth year report [3] for rms and peak forces in wave spectra. The coefficient accounts for duck diameter and duck width (see section () for a precise definition) and therefore serves as a useful comparison with the fourth year work despite the changes in the experimental conditions.

The derived rms force coefficients in fore and aft are shown in figure 3.10. These should be compared with the heave and surge force coefficients in section 5.1.4 and in [3] page 6. It can be seen that they are in close agreement, especially in the larger waves.

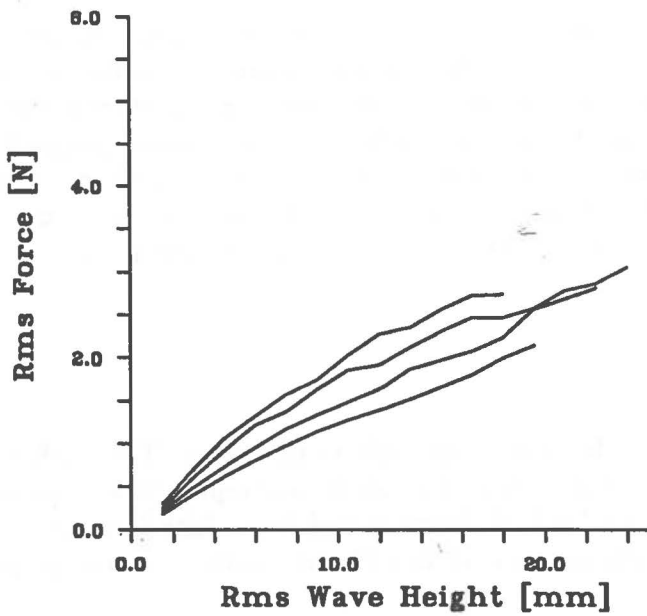
Unfiltered Aft



Unfiltered Fore



Filtered Aft



Filtered Fore

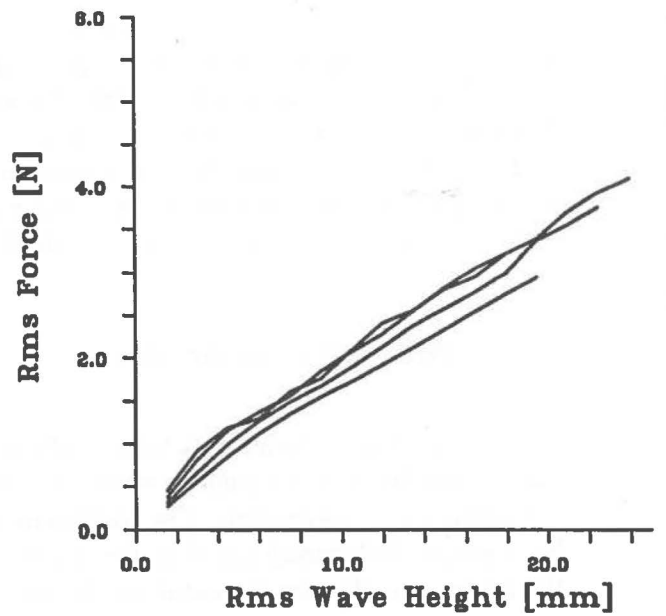
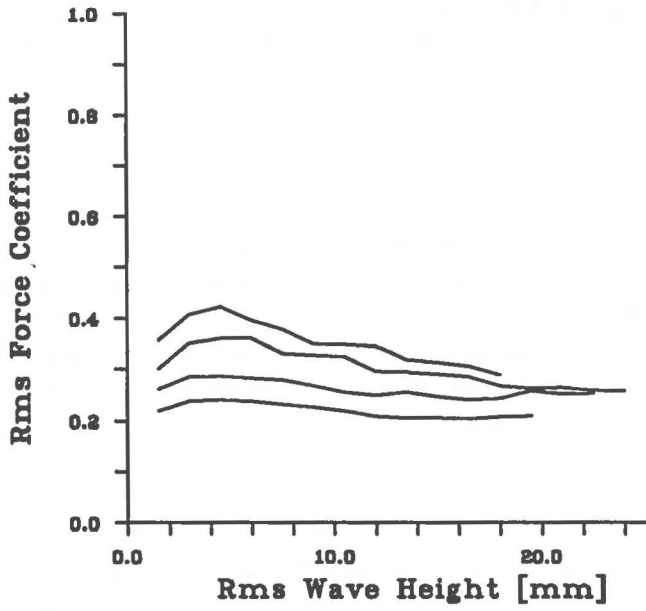
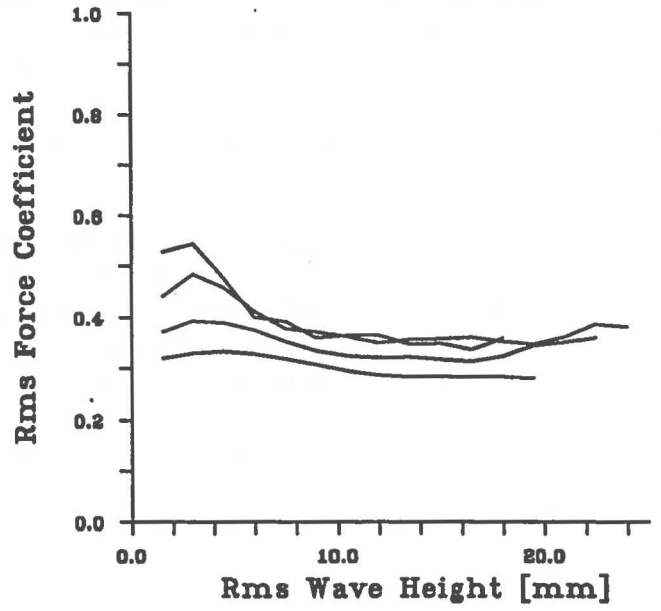


Figure 3.9: Rms forces in Pierson-Moskowitz waves

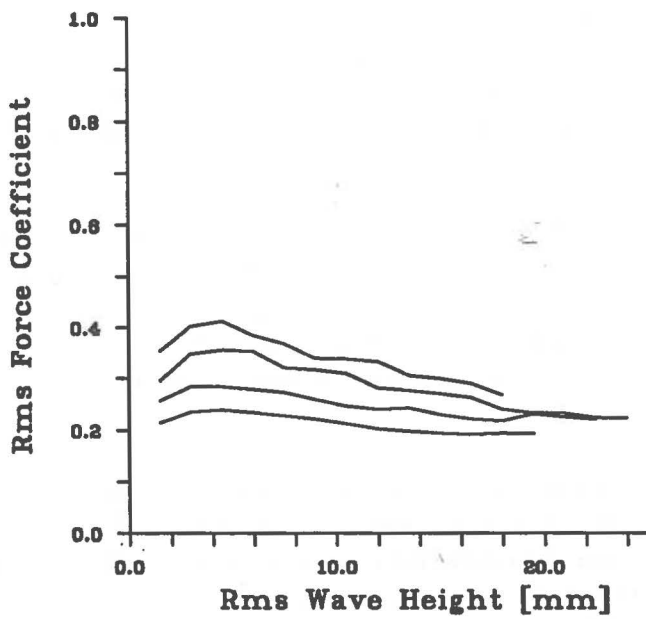
Unfiltered Aft



Unfiltered Fore



Filtered Aft



Filtered Fore

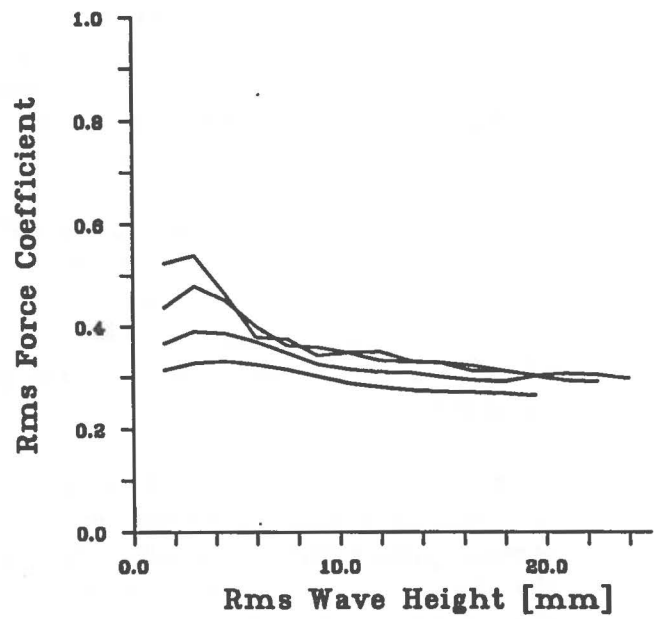


Figure 3.10: Rms force coefficients in Pierson-Moskowitz waves

Note that the coefficients do drop as the wave amplitude is increased, confirming that there is a definite leveling-off trend. It is more difficult to see in the rms plots in figure 3.9.

The trend with wave period is also clearly visible. The shorter waves have the higher wave coefficients (see section 3.2.3) although these converge as the wave amplitude is increased. It is not clear if the coefficients in the very small waves do properly represent the correct linear coefficients. It is possible that a significant contribution is due to stiction and friction in the pitch bearings (see section ()).

3.2.5 Peak-peak/rms force ratios

In the fourth year report [3], a force coefficient for peak forces is introduced. Peak forces are of course of interest in free floating devices where the design of the structure for sustaining these forces is symmetric. The positive peak forces are in the opposite direction to the negative ones and are sustained with an identical but complementary part of the structure or power take-off system. In tension-leg applications, on the other hand, the symmetry is lost and maximum and minimum forces are catered for separately in the design. Even in a design that uses tension/compression legs with a neutrally buoyant device, asymmetries may still exist (e.g. designing to prevent buckling in compression).

It is especially the case that peak forces are of less interest in tension-legs if the high and low peak forces are themselves asymmetric as is the case here. Added to the down force, clipping and snatching make these peak forces highly asymmetric (see section 3.2.2 and figure 3.8).

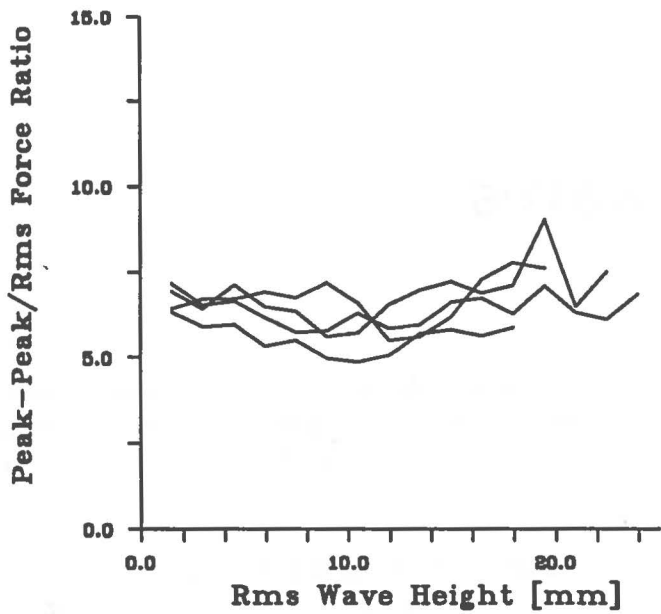
For these reasons and for the purpose of this report, perhaps a more useful coefficient using peak-peak forces should be used. In a tension-leg device the full peak-peak force is, after all, taken in tension. The coefficient would be identical to the rms force coefficient but with peak-peak force and peak-peak wave height replacing rms force and rms wave height respectively (see section ()). It must not be assumed that peak-peak forces are the same as two times peak forces. Even in wave height measurements this assumption is not strictly correct, especially in very steep waves.

To avoid confusion with variations in definitions of force coefficients, the peak-peak/rms force ratios are presented instead. They are shown in figure 3.11. These can then be compared with the measured peak-peak/rms wave height ratios shown in section () and with theoretical predictions of peak-peak/rms wave height ratios for the sampling time (51.2 seconds) and wave periods used here (see section () for these predictions).

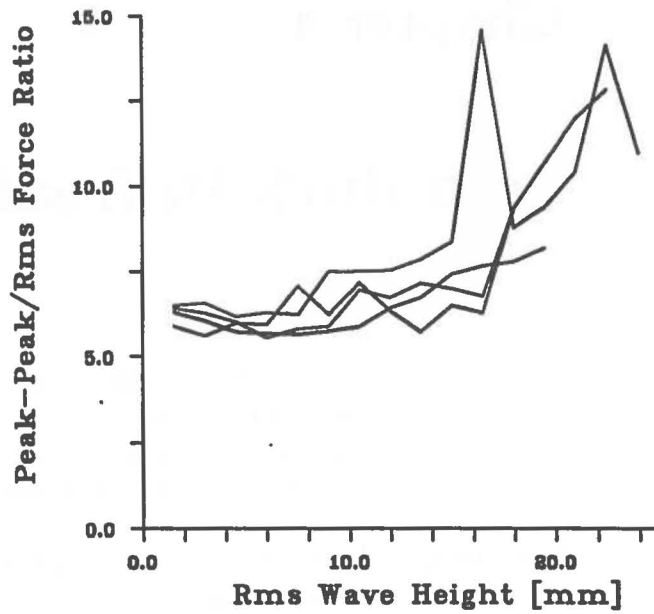
The graphs show that for small wave amplitudes the force derived ratios are broadly the same as the wave derived ratios. This is to be expected as the amplitudes are low enough for linear assumptions to be made. As the wave amplitudes increase the filtered versions of these graphs show a welcome downward trend, especially in aft (the downward trend must be, at least in part, due to clipping when the wire goes slack). The unfiltered ones, on the other hand, can be seen to rise sharply due to snatching.

A peak-peak/rms force ratio of 14.5 (the highest peak in the unfiltered fore graph) corresponds to the maximum force that can be expected over a 2 billion wave cycle period (see section ()). The number of wave cycles within the sampling time for that energy period (0.94 seconds) is about 65. Without the effect of snatching, random wave spectra with a repeat time of over 50 years would have to be generated in the wave tank to measure forces of this magnitude (deliberately arranging the phases of the component waves to produce a freak wave would achieve this much sooner, see chapter 4). In practice no repeat time will produce these forces because of the natural force limiting effects as the wave amplitudes are increased (see sections 4.1.5 and 4.2.4).

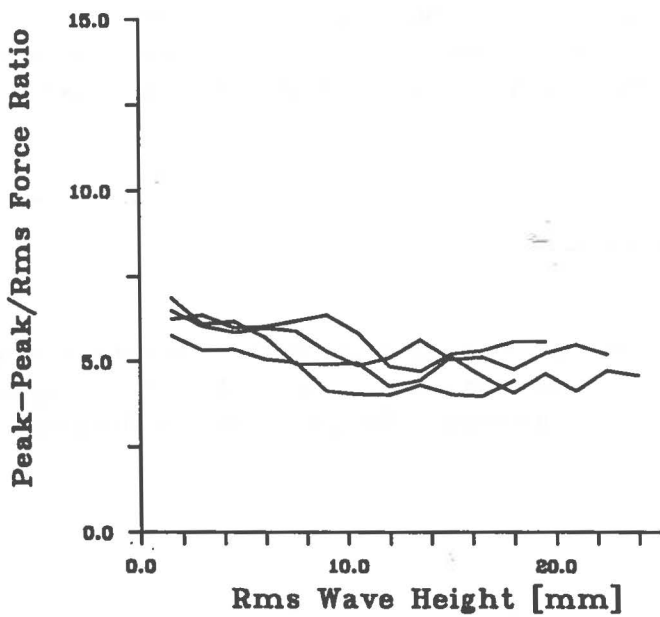
Unfiltered Aft



Unfiltered Fore



Filtered Aft



Filtered Fore

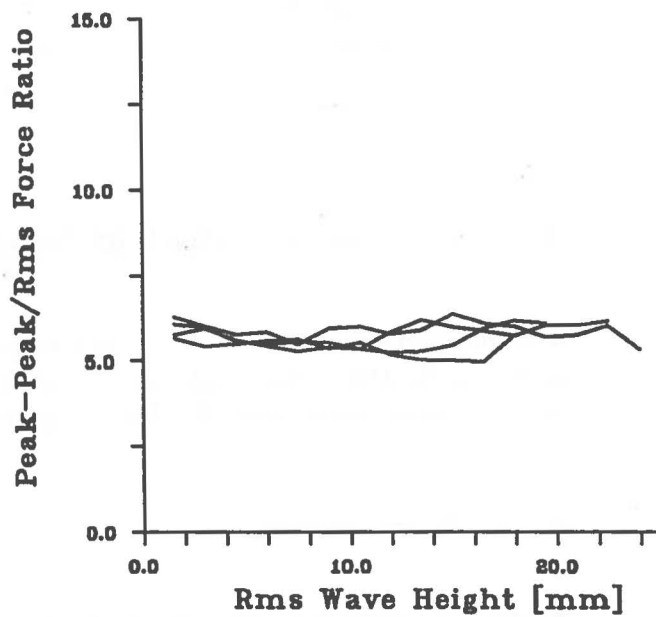


Figure 3.11: Peak-peak/rms force ratios in Pierson-Moskowitz waves

Chapter 4

Solo duck in freak waves

It is impractical to model solo ducks in extreme wave conditions in the same way as the more moderate and much more frequent seas of chapter 3. In the short and medium length waves, amplitudes are limited only by the waves breaking. In long waves, on the other hand, there is an upper limit to the amplitudes that the wave makers can generate (see [5]).

A further difficulty is that in order to get a true representation of the extremely infrequent high wave peaks that are possible in otherwise moderate random sea states, experiments would have to run for very long periods. Fortunately, it is possible to arrange the phases of component waves deliberately, to build a wave with an unusually large peak without having to wait for it to occur randomly. Techniques for doing this have been established for some time now (see [4]). These waves are called freak waves. In the tank they can be generated at will and are very repeatable while at sea they appear randomly and very infrequently. Naturally, if ducks are to survive at sea for long periods, they must be able to survive these waves.

The freak wave that was chosen for these tests has a crest to trough height (about 300mm) that can reasonably be expected within the life time of a duck but it is achieved in a more moderate sea state than would normally be expected for such a large wave (see section () for details). The freak wave also has a period that is in the centre of the useful range where snatching appears to be at its worst (see section 3.2.1).

4.1 The snatch effect in freak waves

The snatch effect in freak waves is much more extreme than in the more moderate conditions presented in chapter 3. The snatch oscillations dominate force records to the point where it is difficult to recognise the underlying wave forces. In this section the effect of snatching in freak waves will be illustrated.

4.1.1 Force records

Figure 4.1 shows force records measured on a duck in a freak wave. The figure shows the forces measured in the fore and aft tension wires as well as the resulting modulus force and its direction. The forces include buoyancy so that in calm water there is a constant force pointing straight up (i.e. 90 degrees from horizontal) keeping both fore and aft wires at the same tension.

The section of the traces at either side of the main snatch events (i.e. below 1 second and above 5

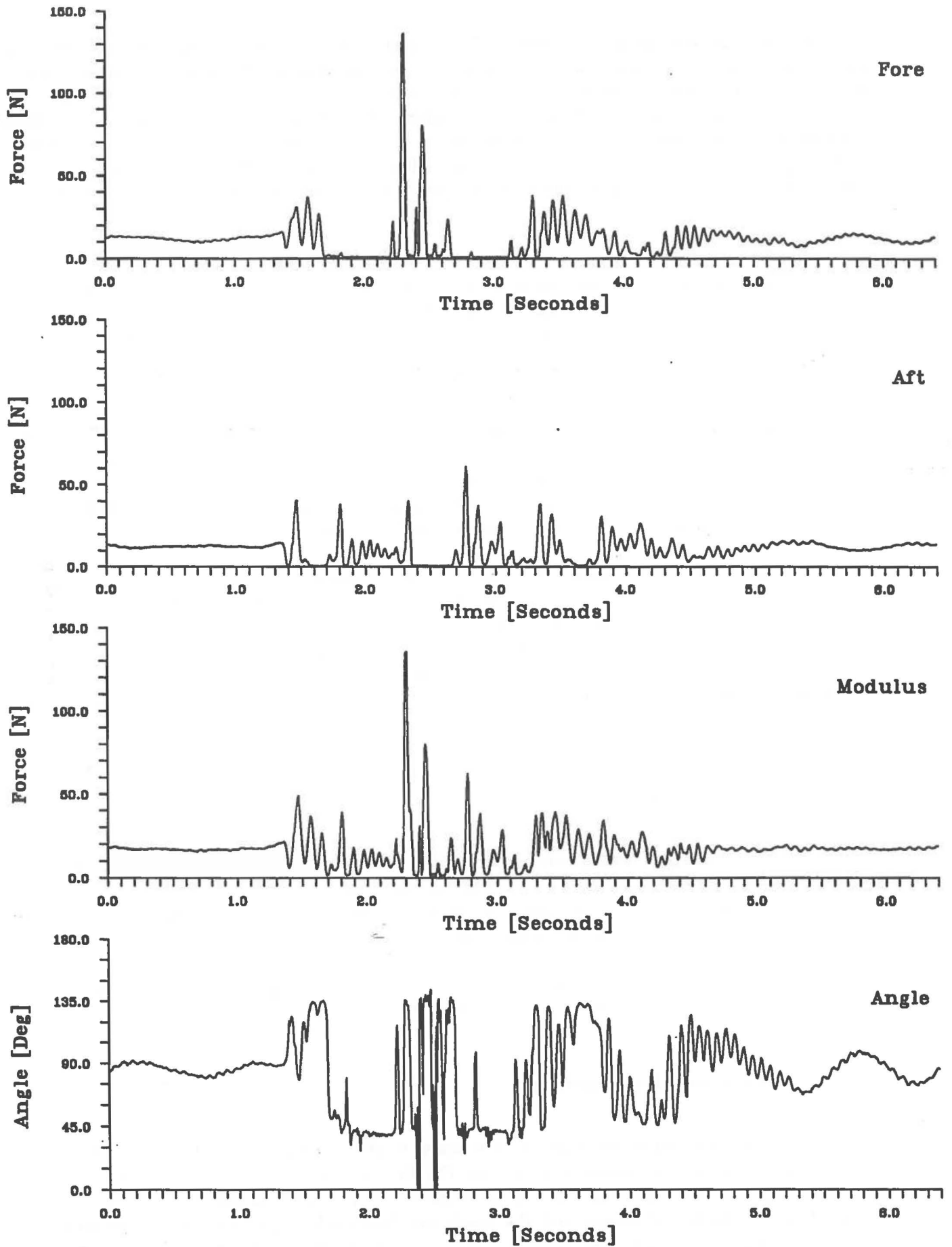


Figure 4.1: Force records measured in a freak wave

seconds) show the underlying wave forces before and after the freak wave. This gives an idea of the wave period (about 1 second). All the oscillations that can be seen with periods below 0.1 seconds are due to the resonance of the mass and added mass of the duck combined with the stiffness of the moorings. The high peaks are caused by the snatching of the mooring lines when tension is restored following a period when the lines have gone slack. It is snatching that induces the high frequency oscillations. Note also the small snatch peaks preceding the main snatch peaks in both fore and aft. These are caused by snatching in one wire first and then immediately followed by the second (see section 3.1.3).

In the fore force record the highest peak force can be seen following the period at around 2 seconds where the wire has gone slack and the measured force is therefore zero. In aft there is a similar but smaller peak following the slack period at around 2.5 seconds. Note that force peaks and oscillations can be induced between fore and aft. The initial fore oscillations are induced by a corresponding brief slack and snatch peak in aft at 1.5 seconds while the peak in aft at 2.3 seconds is caused by the main snatch peaks in fore.

The modulus force record shows the combined magnitude of force from fore and aft. The constant buoyancy force can be seen in the relatively calm periods before and after the freak wave. When the modulus force touches the zero line then both the fore and aft wires have gone slack. The trace shows that this does not happen for any significant duration within a wave period. For most of the time the fore and aft wires alternately exchange periods of slack and snatch oscillation.

The direction of force can be seen to alternate between fore and aft in the record showing the direction of force. Aft is at 45 degrees while fore is at 135 degrees. Note that the modulus and direction are calculated directly from the horizontal and vertical force components of each load cell rather than from the tension in the wire (see section ()). This means that the direction of force can move out with the 45 and 135 degree boundaries when one of the wires has gone slack and the angle of elevation of the other has reduced slightly. The trace also shows some noise spikes when both wires have gone slack and the direction of force is indeterminate.

4.1.2 Snatch force repeatability

Although the snatching effect distorts the underlying wave forces beyond recognition, the effect is nevertheless very repeatable. Figure 4.2 shows the force records measured in four separate runs in otherwise identical conditions. The oscillations do not exactly match but the magnitude of the snatch peaks and the time and duration of the slack and oscillation periods are very close.

The second trace from the top looks as though it is offset in time from the other traces. The most likely explanation for this is that an error has occurred in triggering the start time of sampling.

4.1.3 Freak wave phase variation

Freak waves are produced by arranging for the phases of all component waves to coincide briefly. The phase at which these waves coincide determines the direction of maximum excursion at the specified time and place. Phases of 0, 90, 180 and 270 degrees will produce the highest peak, the maximum forward surge, the lowest trough and the maximum backward surge respectively (see section ()). Phases in between these are also possible. Waves in which the phases are arranged to produce a maximum surge were first proposed by Salter and were named sneak waves.

Figure 4.3 shows a series of fore force records measured in a freak wave with phase incremented in

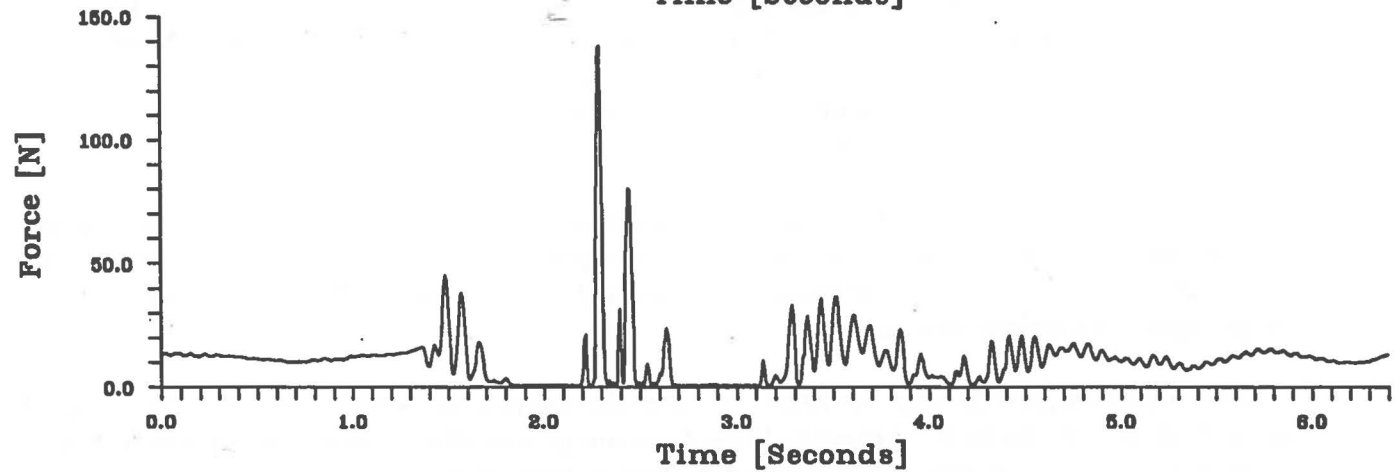
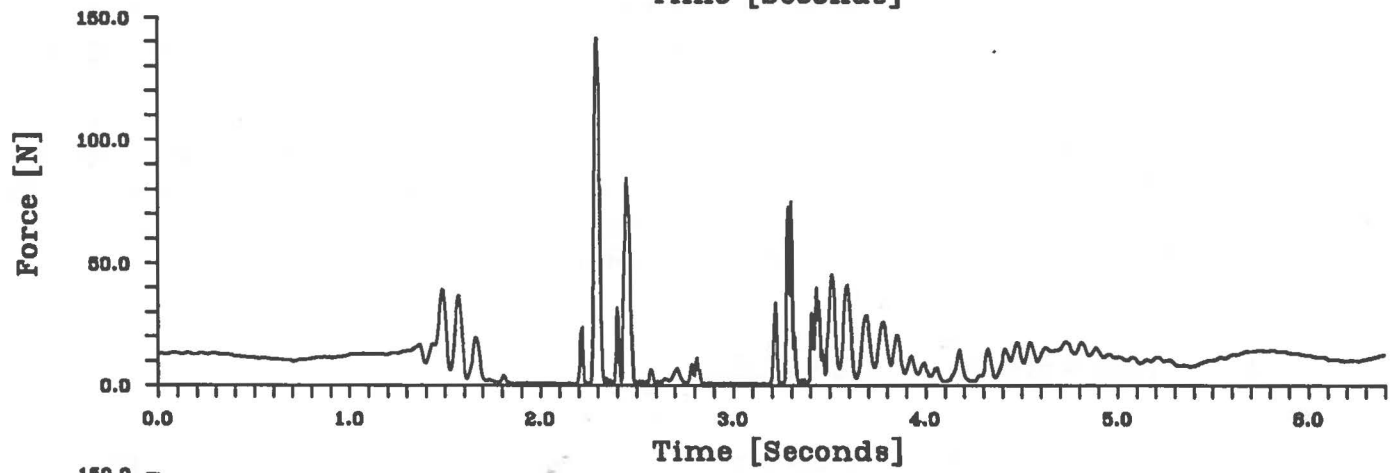
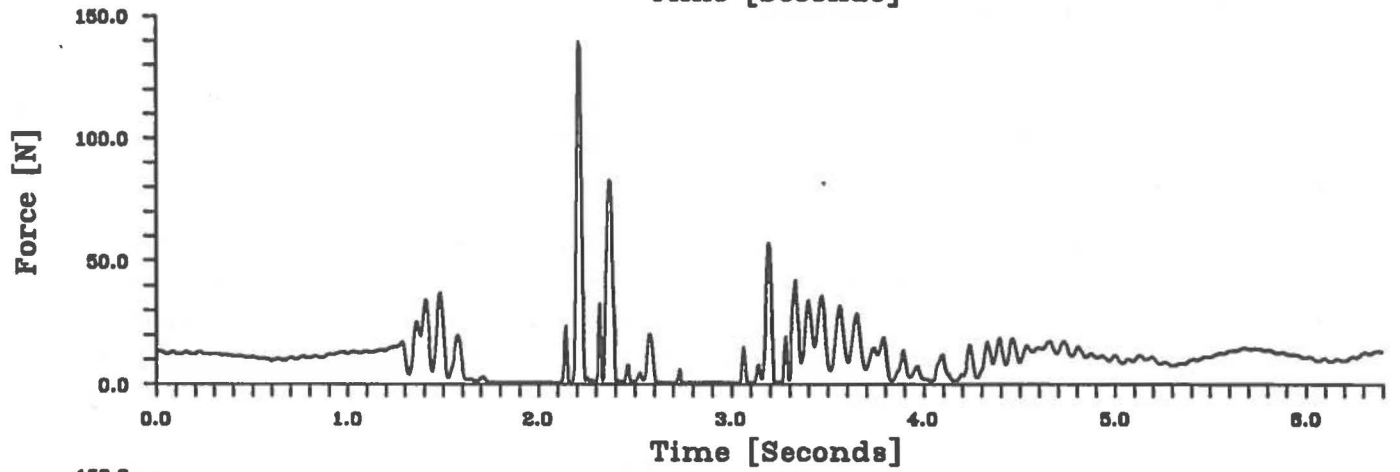
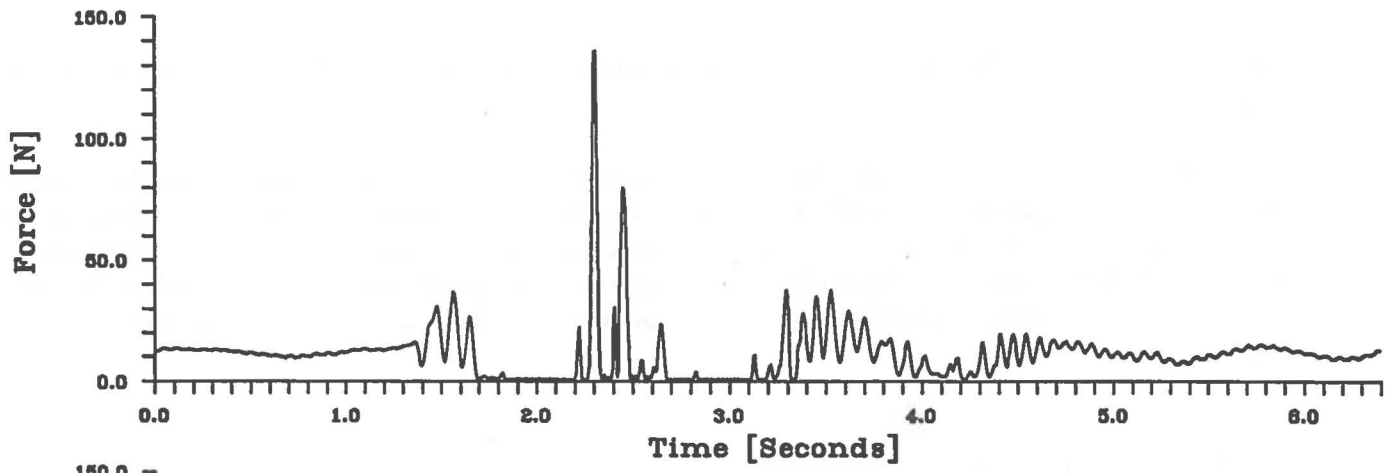


Figure 4.2: Repeatability of force records

steps of 45 degrees. The top trace at zero degrees is a freak crest while the fourth trace is the half way freak trough case.

The records show that the freak events last for several wave cycles. This means that the effect of changing phase is similar to the effect of moving the duck with respect to the wave. Changing the phase, however, insures that duck is always kept at the position of maximum excursion. Although the height of the force peaks are affected by phase change, the main difference is as expected in the times of the slack and oscillation periods. The traces show a very uniform shift in these times with changing phase.

4.1.4 Cartesian view of snatching

Figure 4.4 shows a cartesian plot of forces measured in freak waves. The plot includes the forces from a series of eight records in which the phase of the freak wave was uniformly distributed. The records are the same as those used in section 4.1.3.

Nearly all the sample points appear within the boundaries of a V shape. Inside this V, both fore and aft mooring wires are under tension. The right and left hand boundaries of the V are where the wires have gone slack in fore and aft respectively. The points can actually appear a little outside the V as heave and surge forces are calculated directly from the vertical and horizontal forces measured at each load cell (see section 4.1.3 and ()).

Just above the base point of the V there is a dense cluster of sample points. This is where the buoyancy force is. Most of the points in the cluster are taken from the measurements immediately preceding and following the freak wave.

The plot also shows a dense cluster on the right hand boundary of the V indicating that the fore wire has gone slack for long periods. The large resulting snatch forces can be seen as points reaching far in the diagonally opposite direction (to the left and up). There is a corresponding slack cluster in aft but it is less visible and the snatch forces that it produces are not as severe.

4.1.5 Freak wave amplitude variation

The term 'freak wave' is used to represent an unusually large wave. Two possible applications of this term must be distinguished. One in which it represents an improbable occurrence of an absolute wave amplitude for a given location and another in which it represents an improbable peak-peak/rms wave amplitude ratio. In the latter use of the term a freak wave can in fact be quite small but unusually large for the conditions at the time.

Figure 4.5 shows a series of fore force records measured in freak waves with increasing wave amplitude. All the records are measured in waves that have an equally improbable peak-peak/rms wave height ratio although their absolute amplitudes are increasingly more unlikely. The distribution of absolute amplitudes is dependent on location.

In each of the runs, it is the ratio of the linear sum of the component waves to the rms of the component waves that is kept constant. In practice these wave components do not sum in a linear fashion as the wave increases in amplitude. Wave breaking ultimately limits the actual peak-peak heights.

In the top trace the rms wave height is quite small (2.5mm) but the effect of all the component waves combining together makes the wire nearly go slack. In the next trace there is already a long period

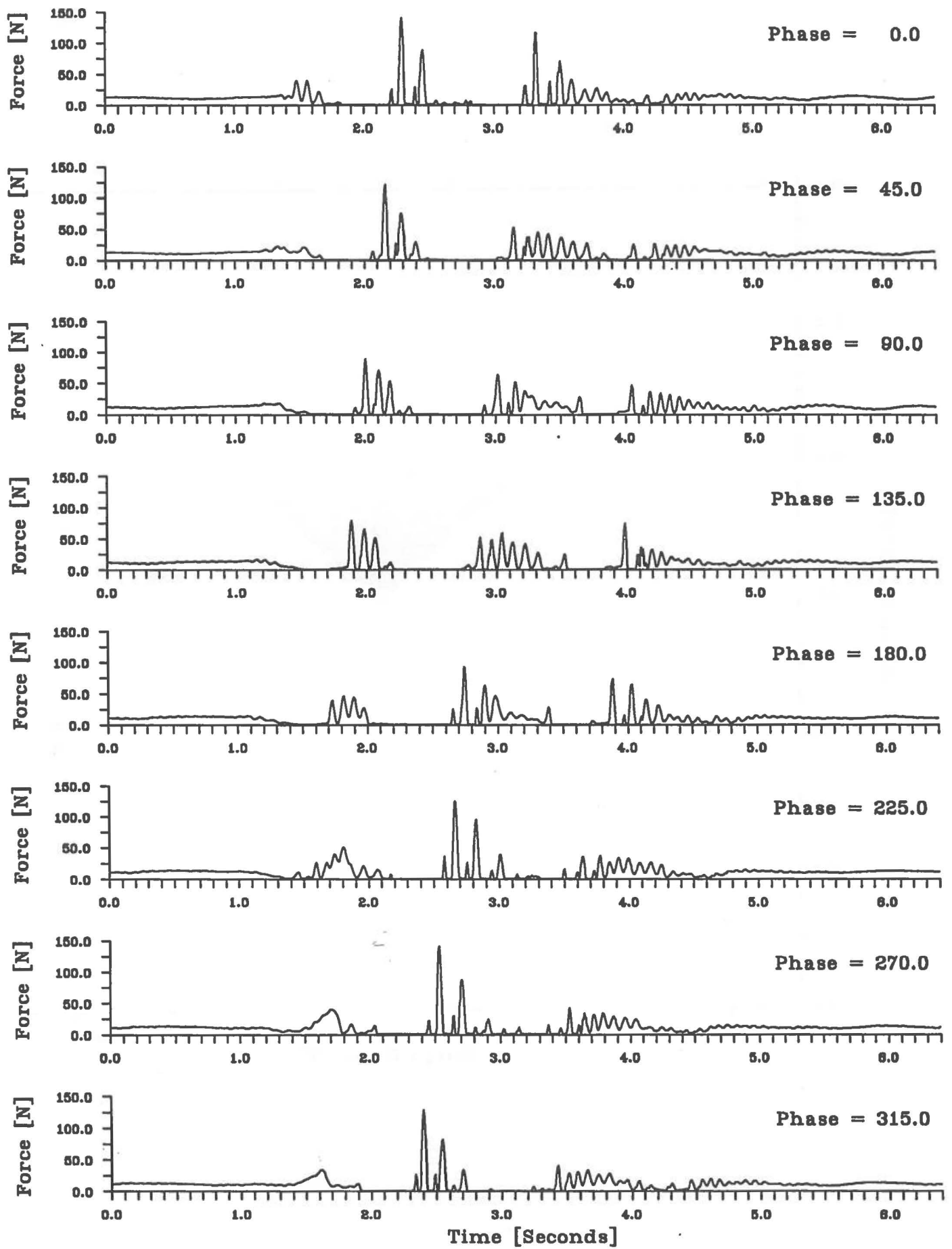


Figure 4.3: Fore force records varying freak-wave phase

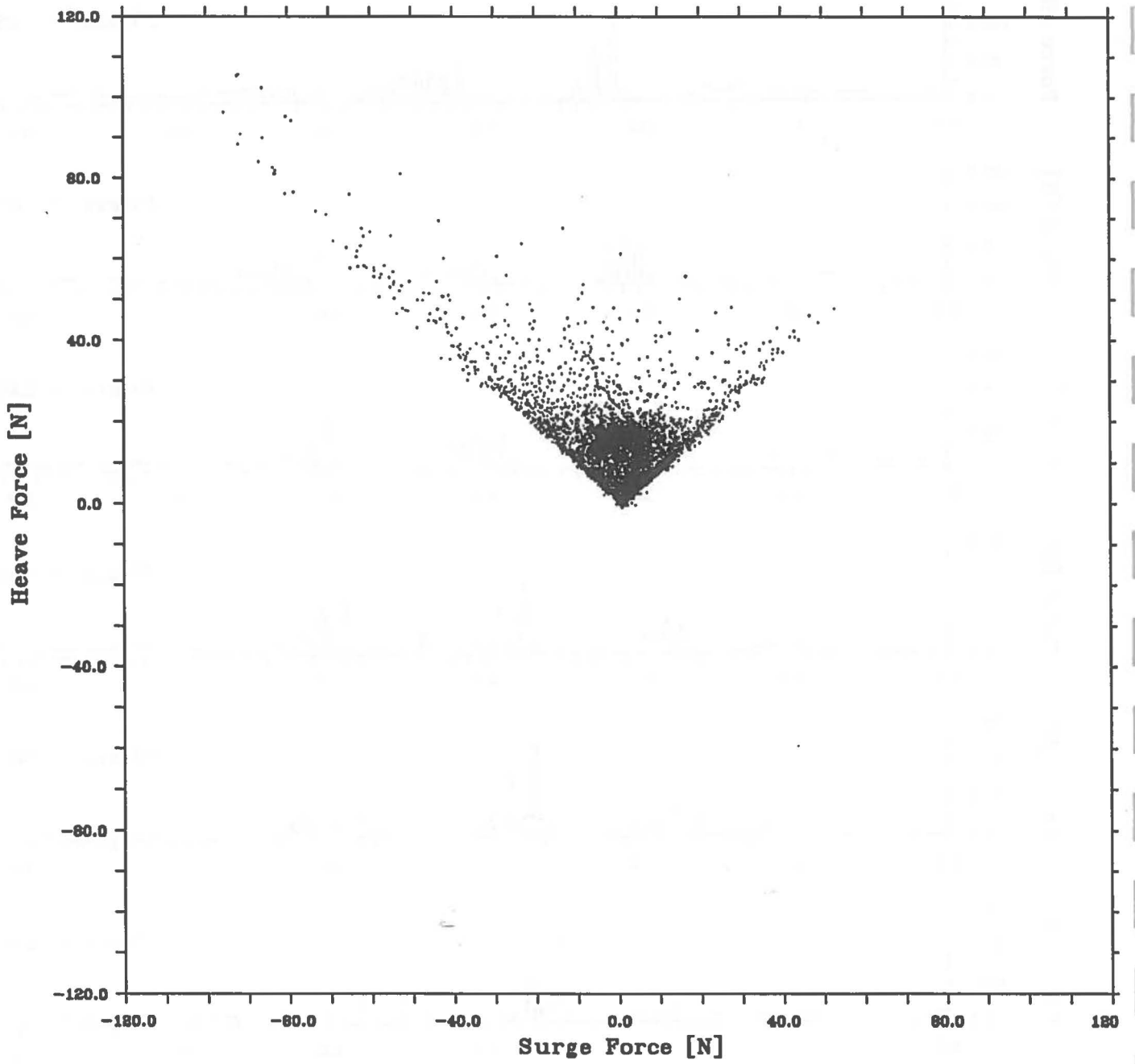


Figure 4.4: Cartesian plot of forces in a freak wave

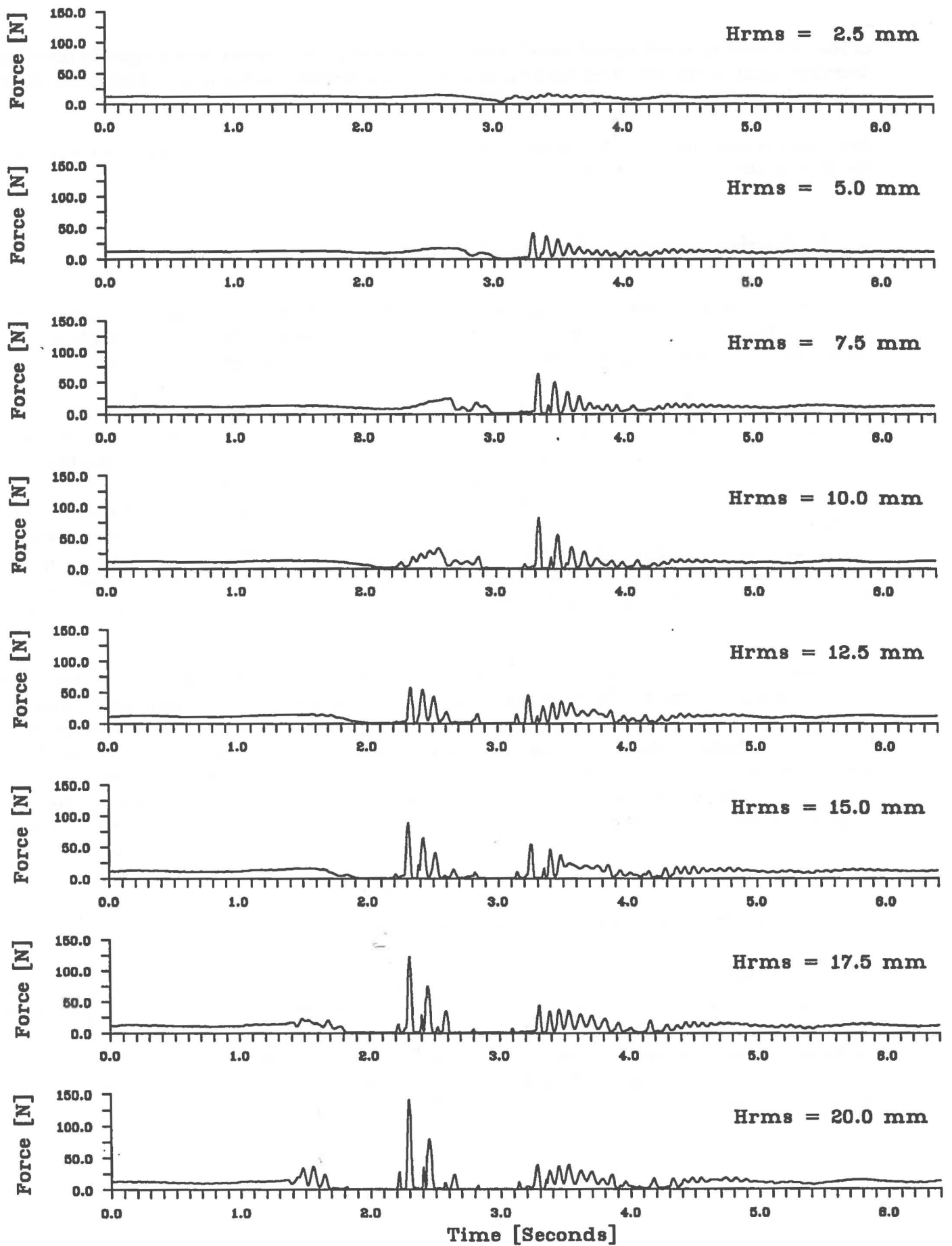


Figure 4.5: Fore force records varying freak-wave amplitude

of slack followed by a substantial snatch force. The snatch peak increases with amplitude but then decreases again as the preceding wave takes over. In the bottom trace it is snatching in aft which induces the initial oscillations (see section 4.1.1).

Note also the small snatch peaks caused by the first of the two wires snatching immediately preceding the main peaks (see section 3.1.3).

4.1.6 Fourier transform of the force records

A fourier transform can isolate some of the various effects that occur in snatching. Figure 4.6 shows spectra of the wave records in figure 4.5. The sampling frequency in these tests is 160Hz so that frequencies up to 80Hz could be isolated. In fact there is no noticeable signal above 25Hz.

The forces that are directly due to the wave spectrum can be seen in each of the graphs at around 1Hz. Most of the display is, however, needed to show the snatch oscillations. In the top trace these oscillations can be seen at around 15Hz (see the small oscillations following the trough in the top trace of figure 4.5). In the second trace the oscillations have moved to a wider band around 10Hz. As the amplitude is increased further, the band of oscillations becomes even wider extending all the way down to 5Hz. Although the stiffness of the moorings remain constant the mass and added mass contributing to resonance are highly dependent on the attitude of the duck in pitch. The 15Hz frequency in the top trace is the resonant frequency of the duck in its calm water position. When the duck has capsized the ballast in the beak contributes to the mass thereby reducing the resonant frequency (see also section 3.1.4).

The main wave spectrum has a lower frequency cut off at about 0.5Hz. Below this frequency no waves are being generated. The force spectrum, on the other hand, shows a significant increase in components well below this frequency. Most of this contribution to the spectrum is due to the down force from the ballast in the beak when the duck has capsized. The capsize attitude is a near stable one so that the duck is often slow to recover from it. This can contribute directly to low frequency components. Capsize and rapid recovery synchronised to the waves will also contribute to these low frequency components indirectly as a result of its effect on the force being so non linear (see also section 3.1.6).

4.1.7 Low frequency contribution to down force

Filtering out all but the low frequency components below the lower limit of wave generation reveals the down force due to capsize (see section 3.1.1). Figure 4.7 shows the low frequency content of the measurements from figure 4.5. The straight line is the calm water tension due buoyancy. Note that all the traces show a reduction in this tension. The figure also shows the largest reduction in tension coinciding with the main slack and maximum snatch periods (see figure 4.5). This is where the duck spends most of its time in its capsized state (see also section 3.1.6).

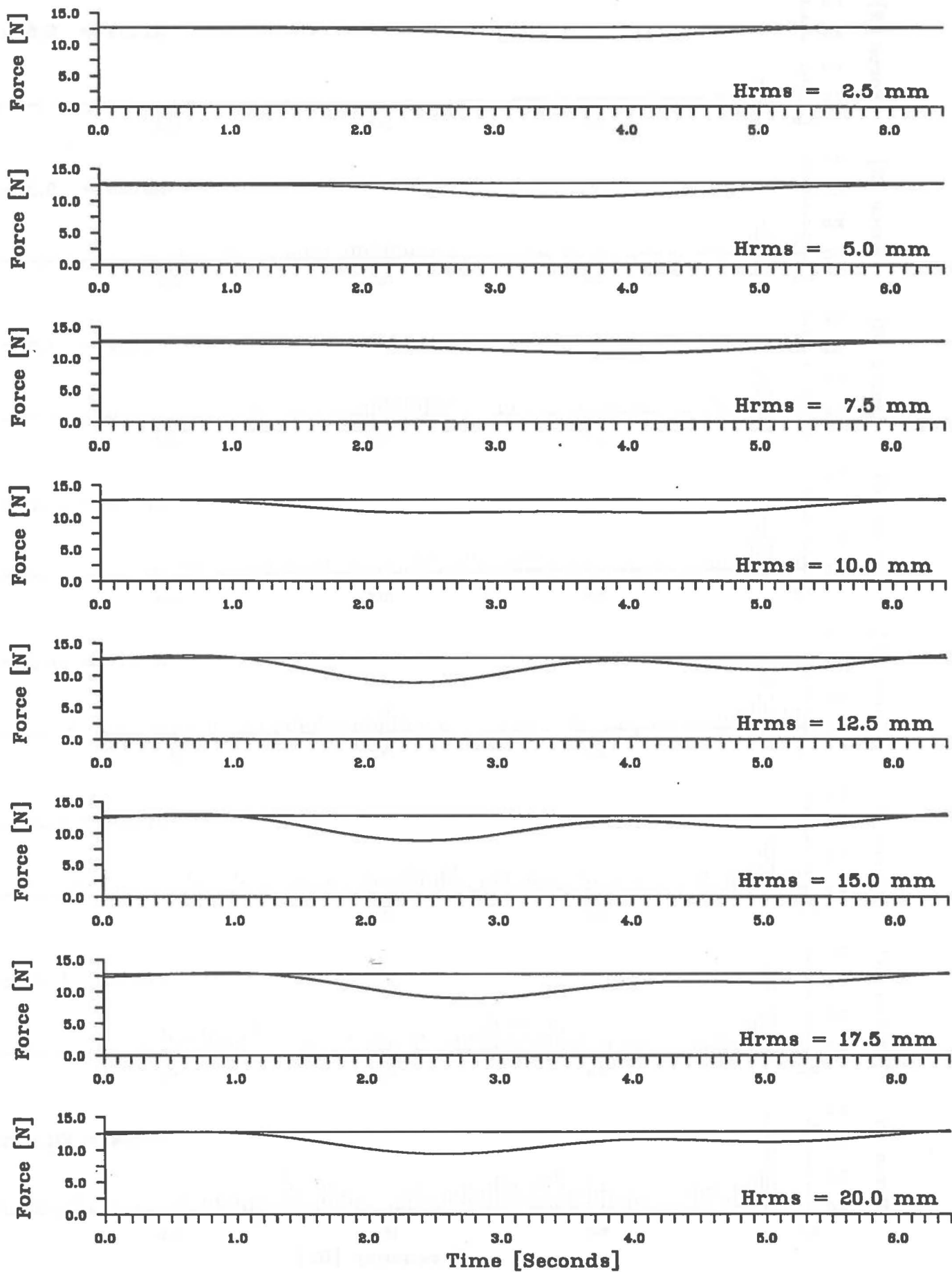


Figure 4.7: Low frequency contribution to force varying freak-wave amplitude

4.2 Force measurement results

Most of the forces presented here are snatch forces and are therefore very dependent on the compliance in the moorings (see section 3.2 and chapter 6).

4.2.1 Maximum force vs phase

The maximum forces in a freak wave can be sensitive to the phase in which all the components coincide (see section 4.1.3 and figure 4.3). Figure 4.8 shows the maximum force as a function of freak wave phase. The horizontal straight line represents the static force due to buoyancy.

The filtered forces are very insensitive to phase while the fore unfiltered snatch force can be halved at certain phases. The maximum snatch force is determined by the effect of the freak wave on the slack period just prior to snatching.

4.2.2 Rms and peak forces

The method used to produce freak waves in the tank combines all the component wave fronts so as their crests coincide at a given time and place. This has the effect of concentrating the large resulting wave into a small number of wave cycles. For the rest of the repeat time of the wave the components cancel each other thereby creating near calm conditions. A measure of rms force in this wave would be based entirely on the short and very non linear freak event. It would therefore not be representative of the rms force that would be measured if the freak wave was properly implemented by a long enough tank run that would achieve the required peak-peak/rms wave height ratio.

A simple way of estimating a representative rms force is to measure it in the same spectrum but with the phases randomised to produce a normal Pierson-Moskowitz wave. In a true representation of very long wave records, the added large waves occur too infrequently to make a significant difference to rms force. Measuring rms force in a short randomised run should therefore produce accurate results. The measurements are in fact obtained from the Pierson-Moskowitz tests from chapter 3.

Figure 4.9 shows the rms forces derived from the Pierson-Moskowitz tests and the peak forces measured in a freak wave. The rms forces are included to give an idea of relative magnitude.

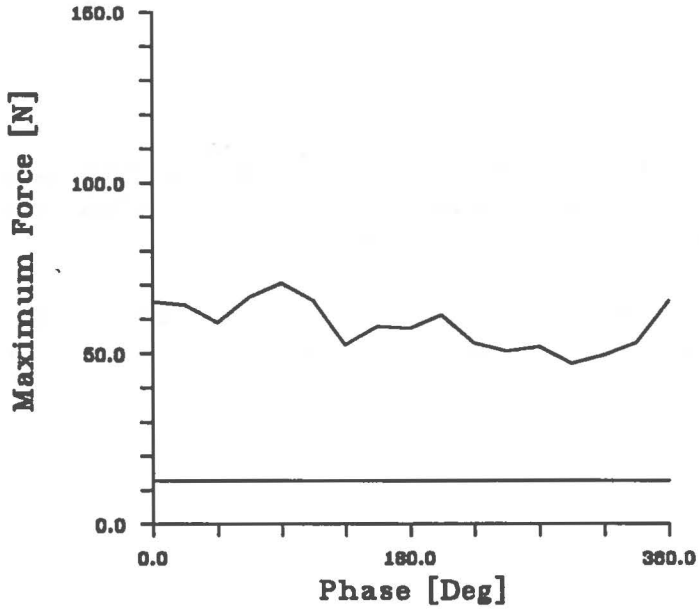
In the fore wire snatching already starts at very low rms wave heights below 4mm while in aft it only appears above 10mm rms wave height. Note that these values depend on the peak-peak/rms ratio of the wave.

4.2.3 Minimum and maximum forces

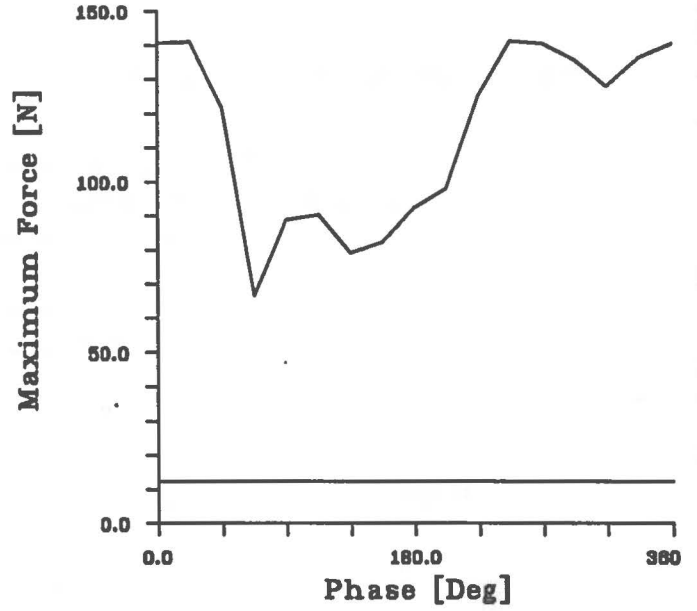
The positive and negative force peaks are very asymmetric (see section 3.2.2). The negative peaks include the down force due to capsize and clipping when the wire has gone slack. The positive peaks on the other hand include snatch forces. Snatch oscillations can also produce negative peaks if the oscillations are induced by slack and positive snatch in another degree of freedom. Figure 4.10 shows the minimum and maximum forces separately. The horizontal straight line is the calm water static force due to buoyancy.

The unfiltered forces show the point at which the lines have gone slack in the minimum forces and the

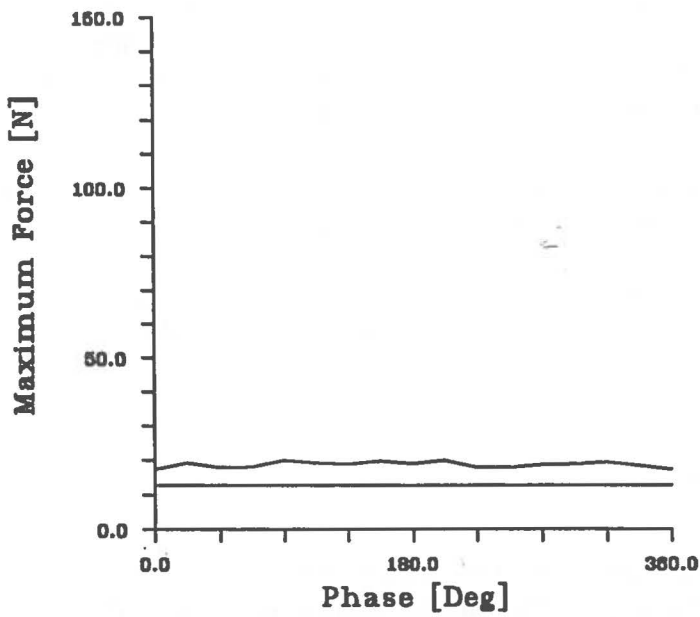
Unfiltered Aft



Unfiltered Fore



Filtered Aft



Filtered Fore

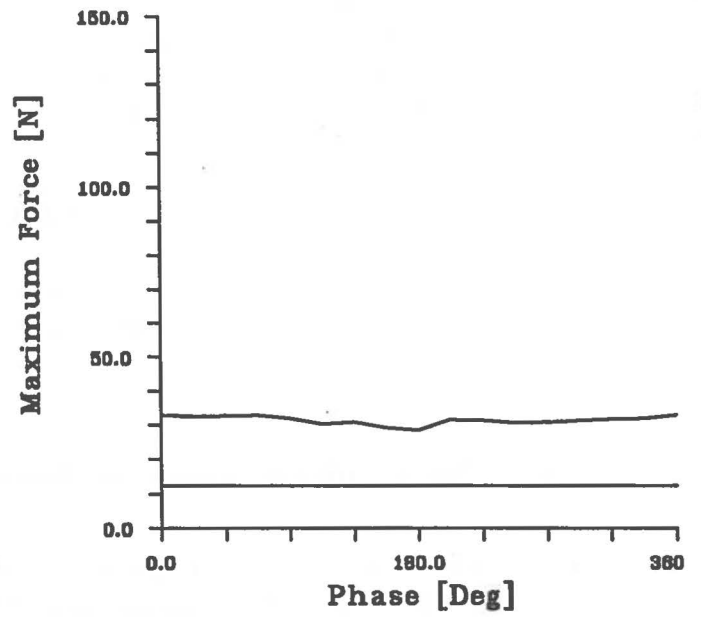
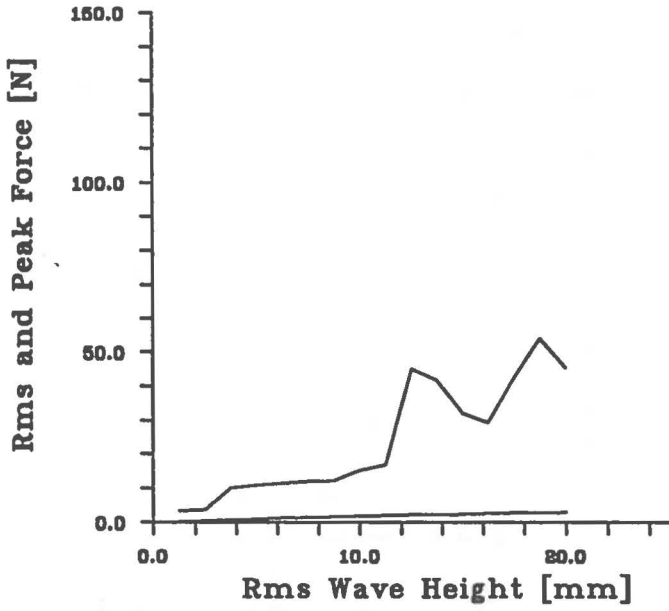
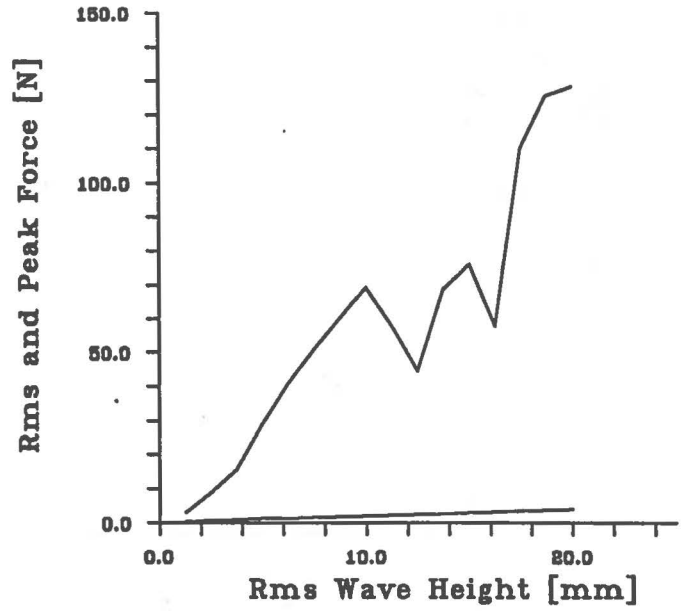


Figure 4.8: Maximum force vs freak wave phase

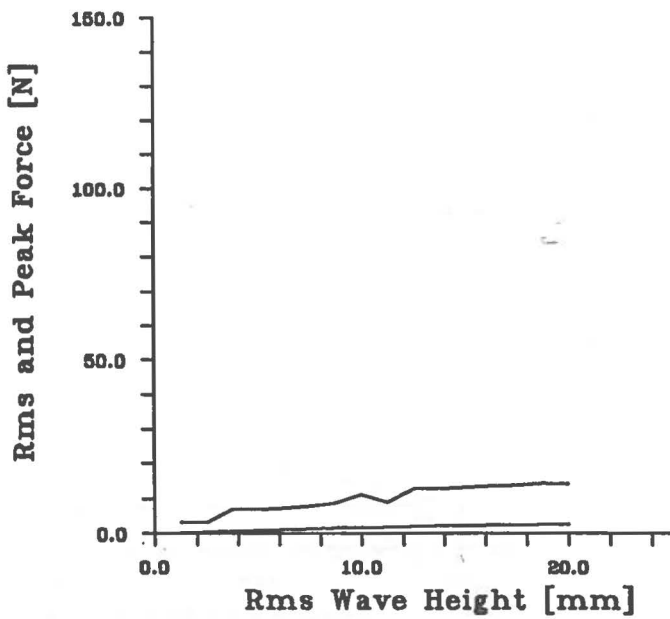
Unfiltered Aft



Unfiltered Fore



Filtered Aft



Filtered Fore

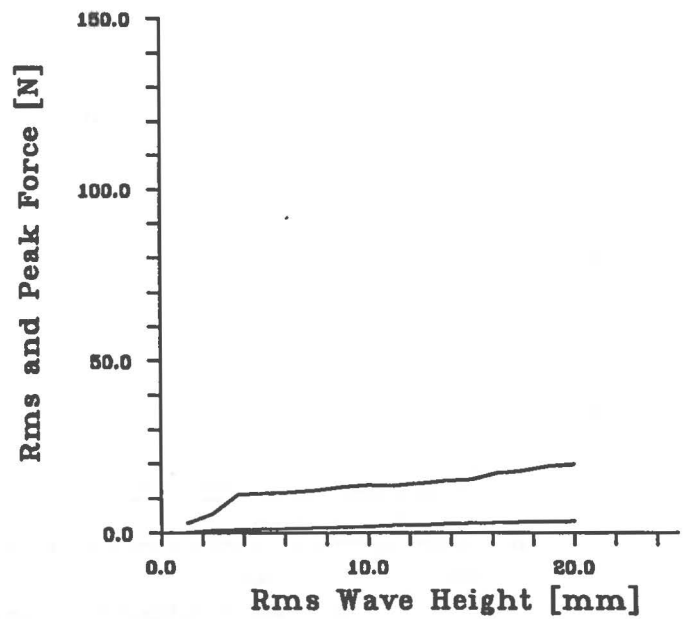
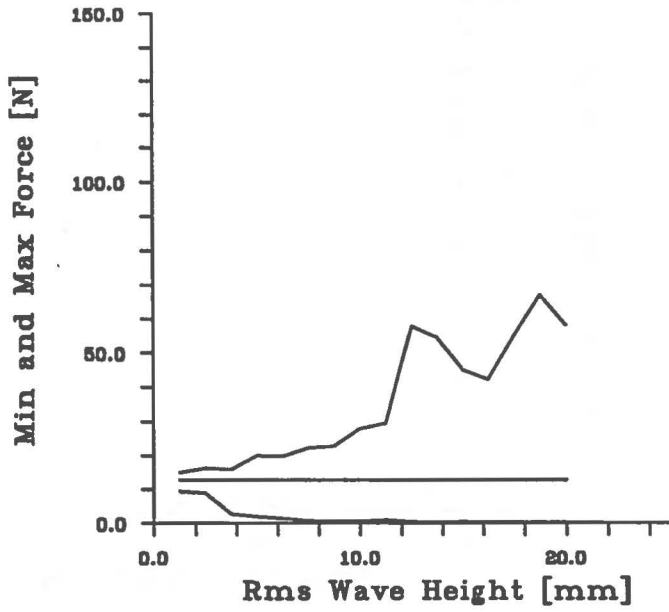
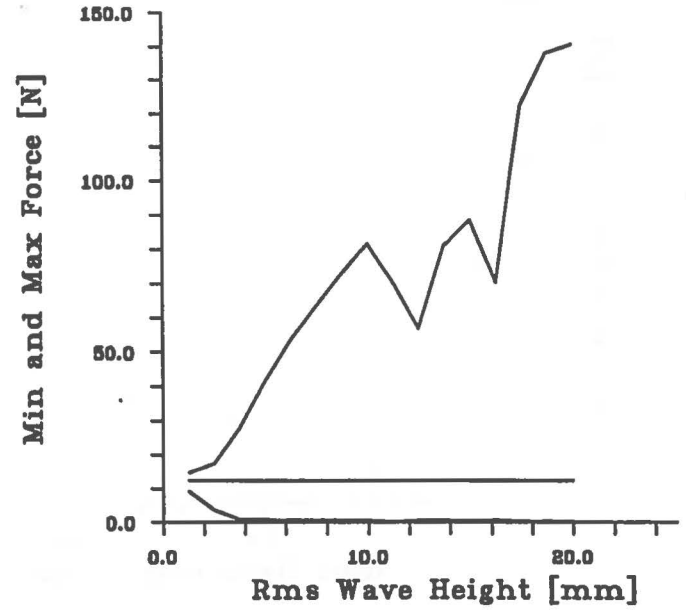


Figure 4.9: Rms and peak forces in freak waves

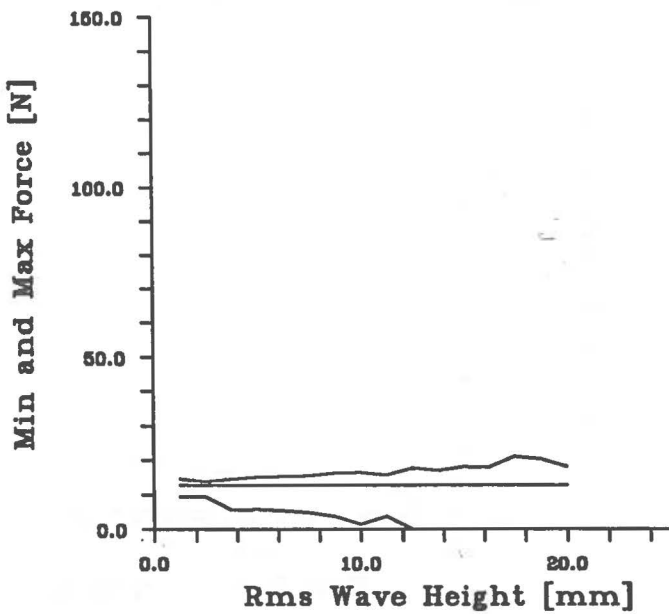
Unfiltered Aft



Unfiltered Fore



Filtered Aft



Filtered Fore

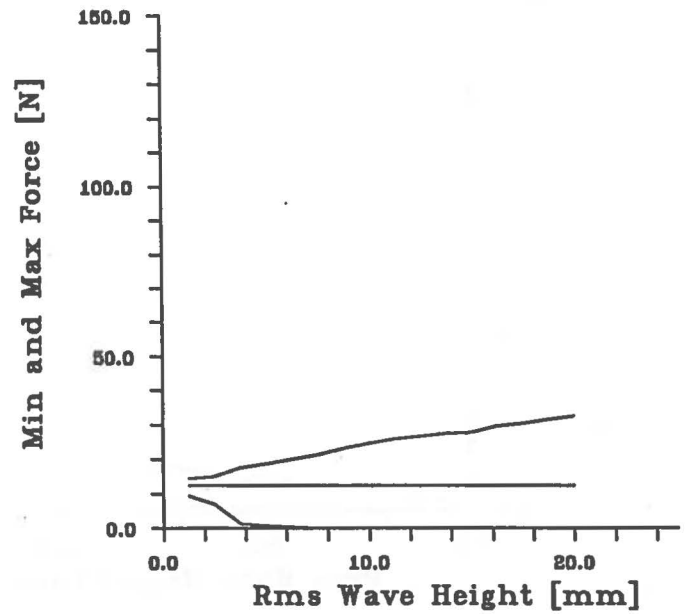


Figure 4.10: Minimum and maximum forces in freak waves

corresponding snatch peaks in the maximum forces. In fore the wires go slack below 4mm rms wave height while in aft the wires only go slack above 10mm rms wave height. Note also the difference in the forces in aft between the unfiltered and the filtered forces. From about 4mm up to about 10mm rms wave height the the unfiltered positive and negative peaks are due to oscillations induced by snatching in fore. Above about 10mm rms wave height the oscillations rise sharply as they are directly induced by snatching after a slack period in aft.

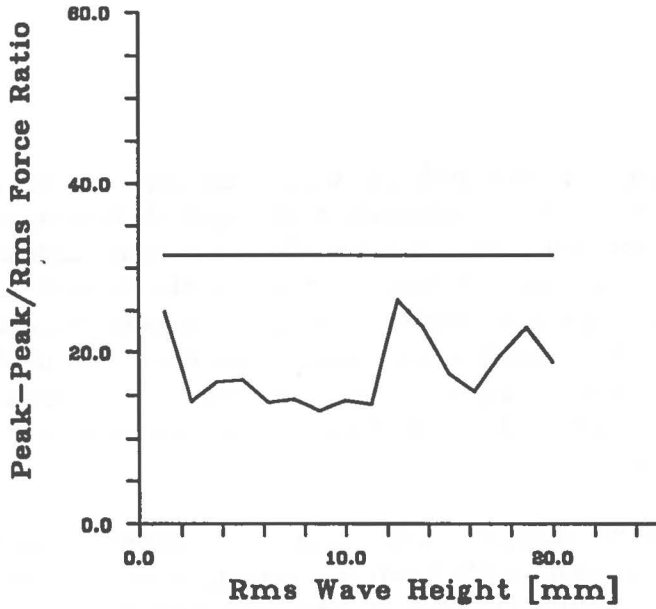
4.2.4 Peak-peak/rms force ratios

The freak wave used in these tests has a unusually high peak-peak/rms wave height ratio in order to achieve a large wave in otherwise moderate conditions. As the generated wave amplitude is increased the actual peak-peak height is limited by non-linearity and in particular breaking. This effect combined with leveling-off of forces with increasing actual peak-peak wave height implies that the forces should display a strong leveling-off trend with increasing rms wave height. The measured peak-peak/rms force ratios should not reach the peak-peak/rms wave height ratios based on the linear sum of the component waves. Note that the rms forces used to calculate the peak-peak/rms force ratios are the underlying rms forces in a representative sea with randomised phases and are derived from the Pierson-Moskowitz tests from chapter 3 (see section 4.2.2).

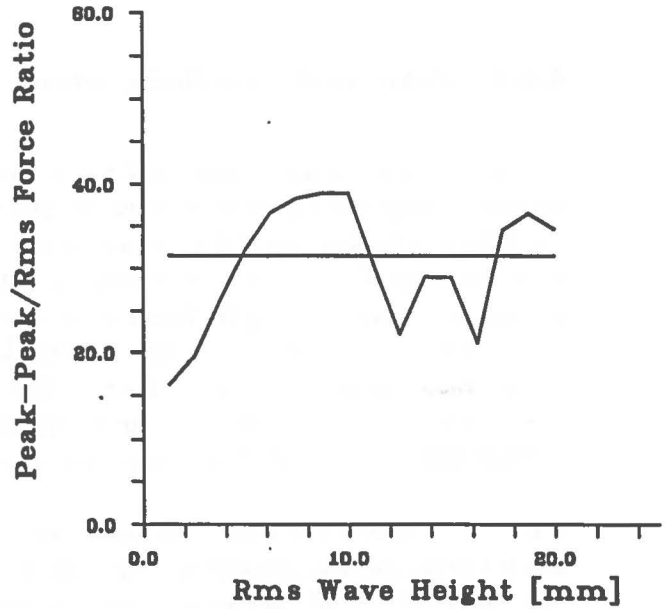
Figure 4.11 shows the peak-peak/rms force ratios measured in a freak wave. The horizontal straight line is the theoretical peak-peak/rms wave height ratios based the linear sum of components. Although this ratio (about 30) makes this wave extremely unlikely (theoretical mean time between events of about 6 billion years; approximately the age of the earth, see section ()), a comparison between this ratio and the force ratio is nevertheless instructive.

The forces with snatching filtered out show the expected down trend with increasing rms wave height. With snatching included the forces can exceed the theoretical ratio although they to exhibit a down trend. The large dips in the ratios are caused by the sensitivity of the snatching effect to the position of wave breaking. As the amplitudes are increased the main snatch peaks are moved in time (see figure 4.5). The effect is similar to the effect of changing freak wave phase (see figure 4.3).

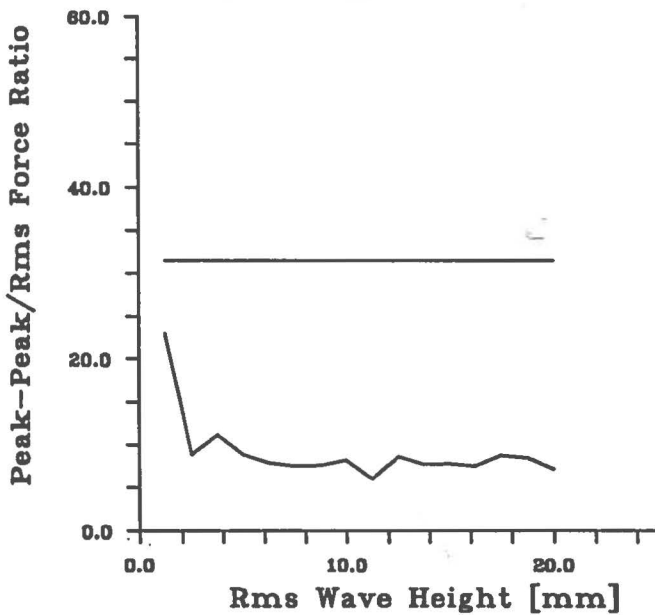
Unfiltered Aft



Unfiltered Fore



Filtered Aft



Filtered Fore

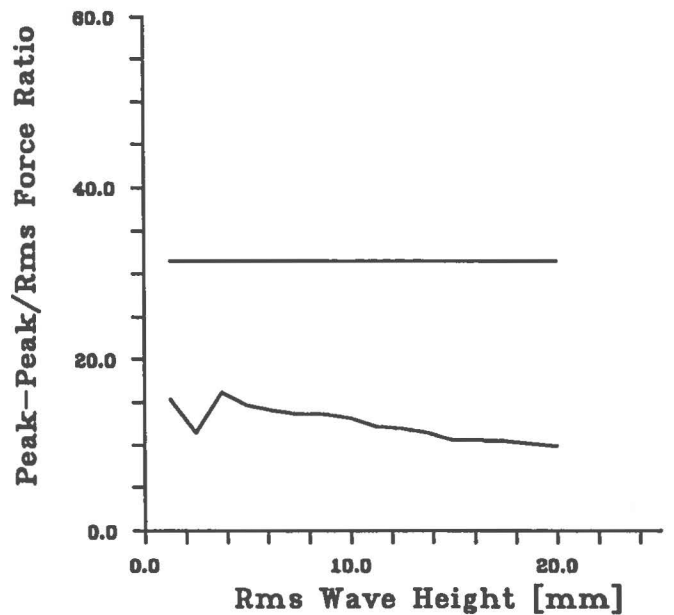


Figure 4.11: Peak-peak/rms force ratios in freak waves

Chapter 5

Comparison with fourth year work

Wave power devices that react against the sea bed are likely to use diagonal tension legs for power take-off. A diagonal arrangement is needed for controlling movement in all degrees of freedom. It is for this reason that all the measurements and the results so far have been done for a fore and aft tension-leg configuration. While this will almost certainly be the most likely arrangement at full scale, it is nevertheless useful to present heave and surge results for comparison with the fourth year work [3, 4]. The heave and surge forces have not been measured directly but have been derived from the fore and aft records. The results can be compared with the fixed heave and surge tests in the fourth year work but only as long as tension is sustained. At wave heights that cause the lines to go slack the comparison breaks down and it becomes inevitable that the results will diverge.

As in the previous chapters, all the results are presented using both the filtered and unfiltered force records. This gives a useful comparison between the effects of snatching and the results that may be expected if snatching did not occur.

5.1 Pierson-Moskowitz wave results

The standard duck configuration (see section ()) is used here to derive the heave and surge equivalents of the results presented in chapter 3.

5.1.1 Rms and peak forces

Rms and peak forces were measured for the fourth year work [3] on a duck that was fixed in heave and surge but with a torque limit applied in pitch. Torque limits were set to suit the requirements of cost effective power take-off and were therefore much lower than the torques that would be needed to keep the duck fixed in pitch. The results showed little dependence on the torque limit applied. The tests for this report were done on a duck that was free to move in pitch and the results should therefore be close to the measurements made with the lower torque limits (see page 2.54 and 2.61 in [3]). Torque limit should not play a major part in the difference between the test results.

Although the test conditions are very similar, there are nevertheless some important differences. The tests here were done on a solo duck in a wide tank and at a different scale. The size of the model at tank scale is the same in both cases although the waves were adjusted to represent the same conditions at full scale for a 10 metre diameter duck. Note also that total force is presented in these graphs rather than force per unit width which is more appropriate to a string of ducks. The graphs presented in this

section would be best used for qualitative comparison. A quantitative comparison is best made using the derived force coefficients in section 5.1.4.

Figure 5.1 shows heave and surge rms and peak forces for the standard test case. Note that the scale of the graphs had to be chosen to accommodate the large snatch peaks. The underlying peak forces are much smaller by comparison. The rms forces are included to give an idea of relative magnitude.

Apart from the snatch peaks, the most striking result in the graphs is the difference between heave and surge for intermediate wave heights. The surge peak forces follow a smooth curve and show a leveling-off trend up to the point of snatching. The heave forces, on the other hand, rise more slowly to start with but then diverge and rise sharply. The same trend can be seen in the fourth year results (see [3] pages 2.52 to 2.65). The phenomenon is due to the down force during duck capsize (see sections 3.1.1 and 3.2.2).

5.1.2 Minimum and maximum forces

Separating the positive and negative peaks gives a more clear view of the asymmetry in the heave forces. Figure 5.2 shows the heave and surge minimum and maximum forces. The horizontal straight line represents the calm water force due to buoyancy (zero in the surge case).

The graphs show that the surge peaks are smooth and highly symmetric up to the point of snatching while the heave forces show that it is an added down force that is responsible for the divergence of the peak forces in figure 5.1. Note how small the positive peaks are compared to the negative peaks.

5.1.3 Rms forces

Figure 5.3 shows the rms forces from figure 5.1 on an expanded force scale. The unfiltered and filtered forces are very similar although they differ slightly in magnitude. This indicates that snatching events do not significantly alter the underlying rms forces.

The difference between heave and surge, on the other hand, is much more striking. Surge forces rise smoothly and display a leveling-off trend while the heave forces diverge significantly with period. The shorter periods produce the larger rms forces. Much of the difference between the periods is due to the contribution to rms force from the added down force. The water particles have a higher velocity and acceleration in shorter waves for a given wave height and are therefore more likely to cause capsize.

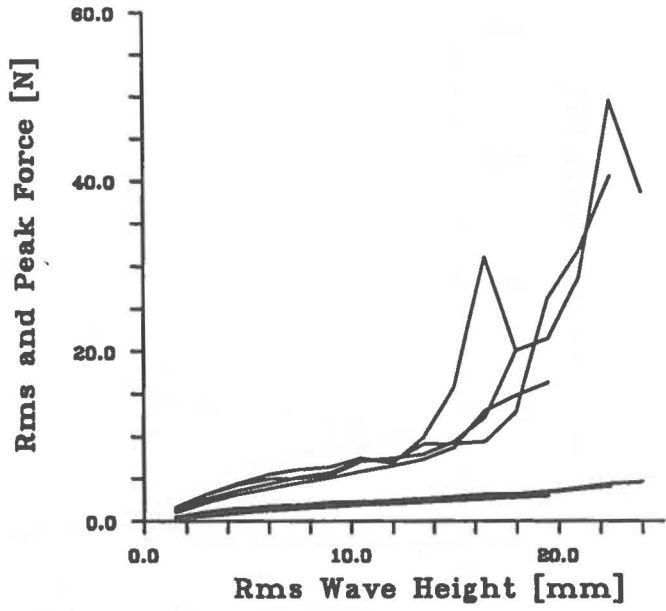
5.1.4 Rms force coefficients

The most important comparison between the this work and the fourth year work is in the rms force coefficients. For the coefficient to be useful it must account for the difference between the test conditions.

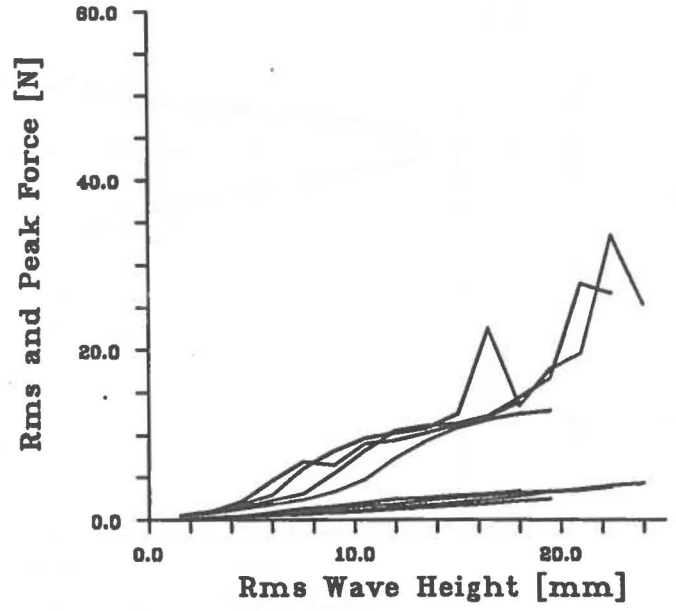
Figure 5.4 shows the derived heave and surge force coefficients. These should be compared to the force coefficients in [3] page 2.6 on the left hand side of the page but see also all the force coefficients combined on page 2.5. It is clear that despite the differences in test conditions the result do broadly agree. Surge force coefficients start at about 0.5 and drop gently to 0.3 with increasing wave height while heave coefficients start at about 0.2 and rise gently to about 0.3.

The main discrepancy between results is in the heave force coefficients in the mid range wave heights.

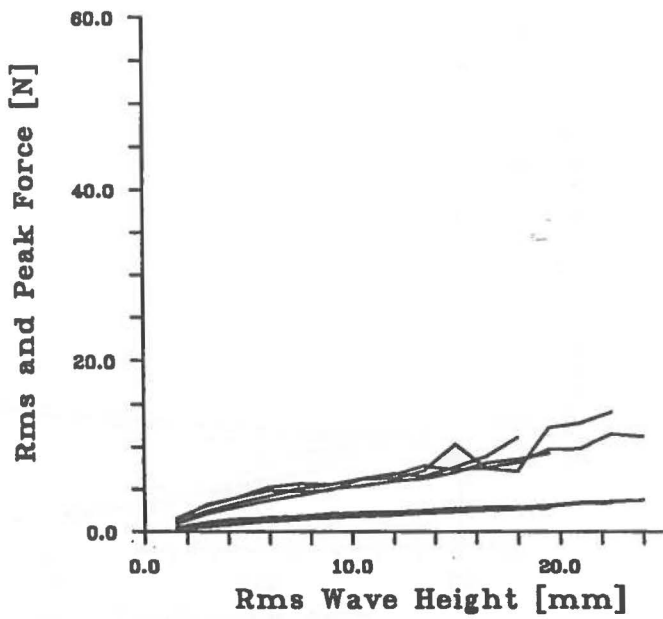
Unfiltered Surge



Unfiltered Heave



Filtered Surge



Filtered Heave

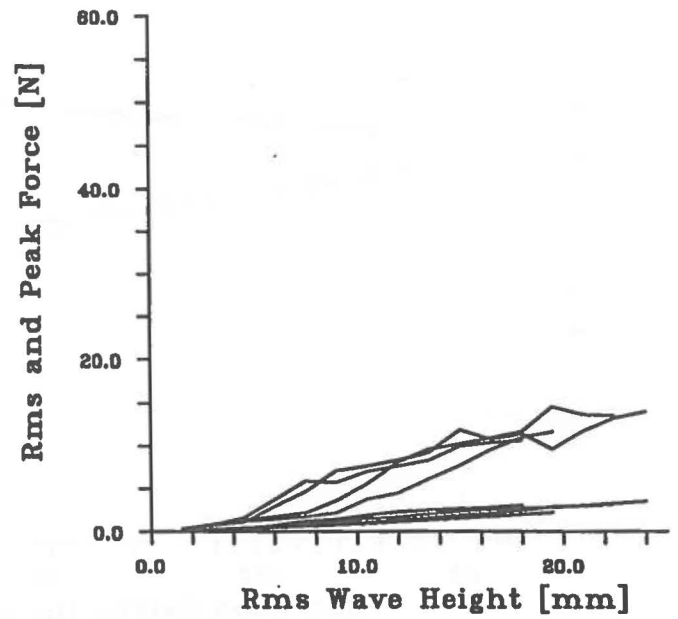
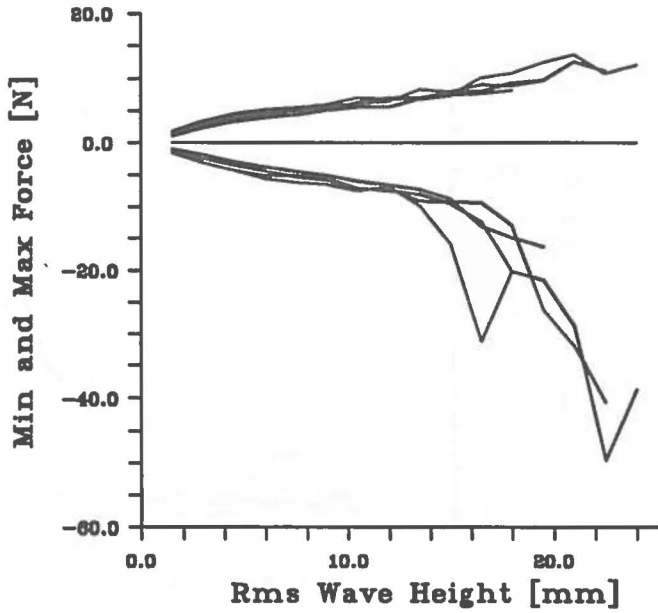
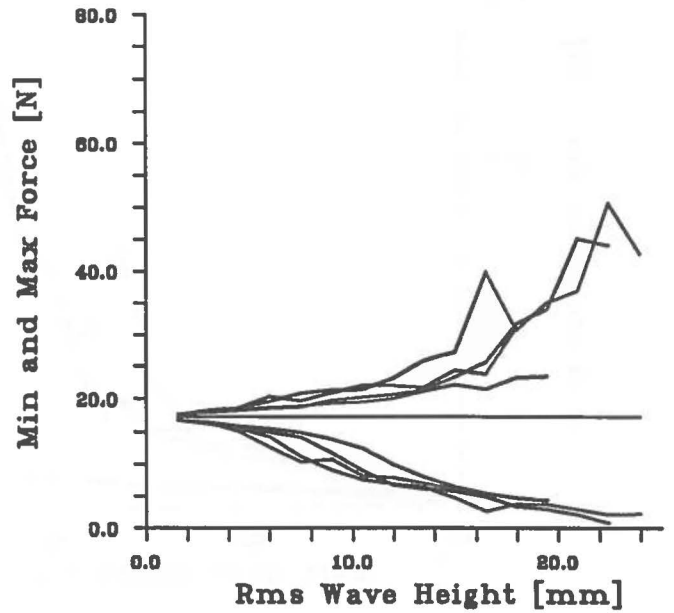


Figure 5.1: Heave and surge rms and peak forces in Pierson-Moskowitz waves

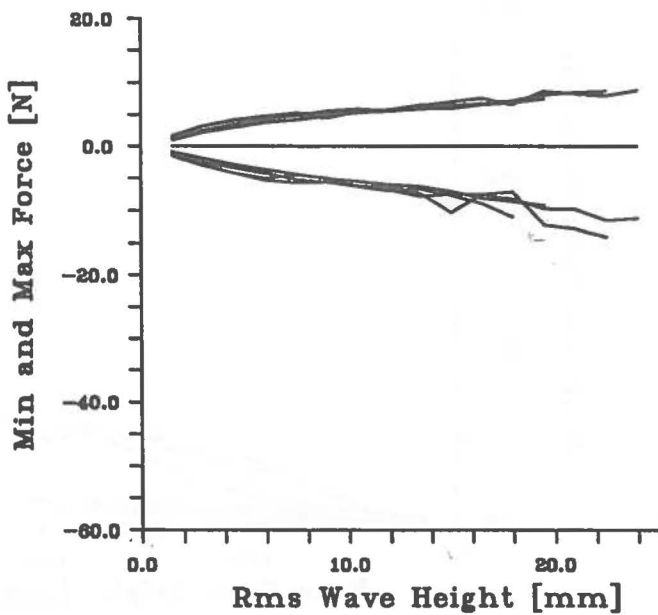
Unfiltered Surge



Unfiltered Heave



Filtered Surge



Filtered Heave

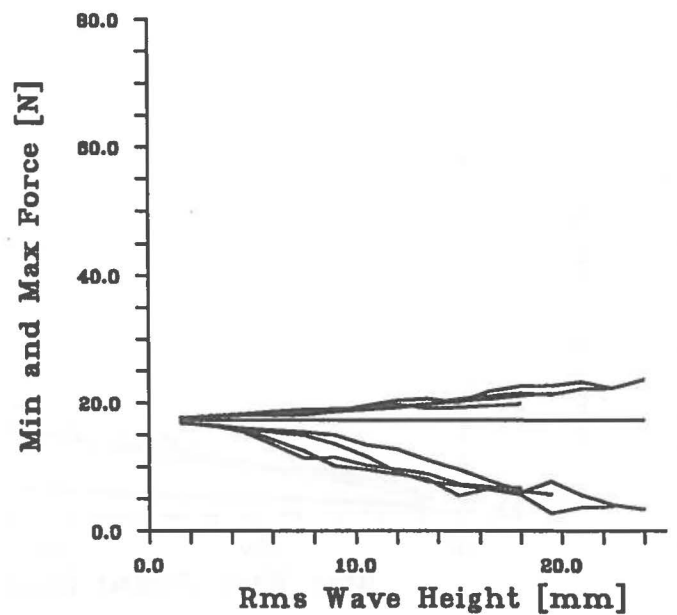
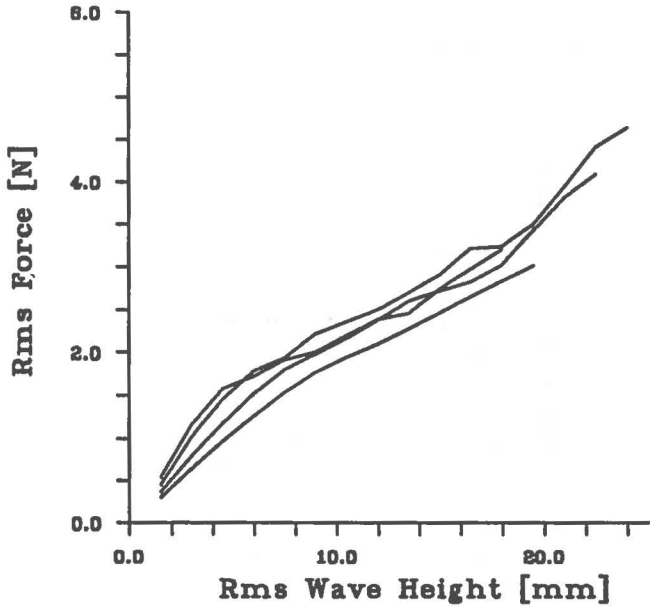
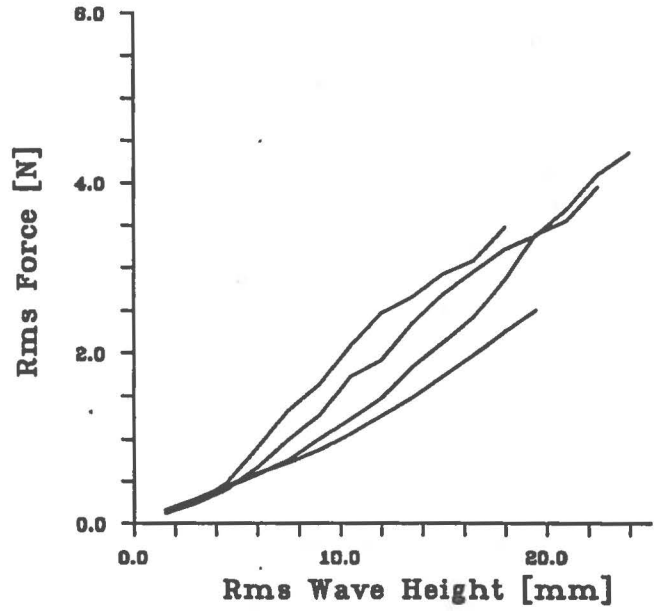


Figure 5.2: Heave and surge minimum and maximum forces in Pierson-Moskowitz waves

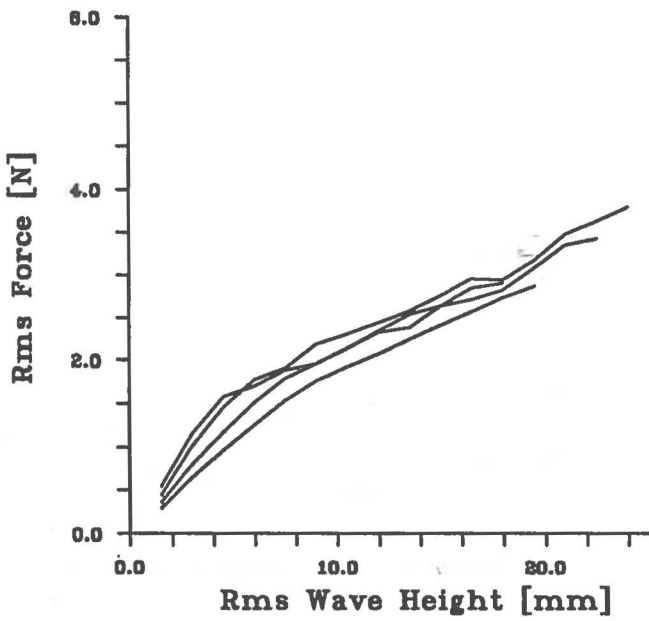
Unfiltered Surge



Unfiltered Heave



Filtered Surge



Filtered Heave

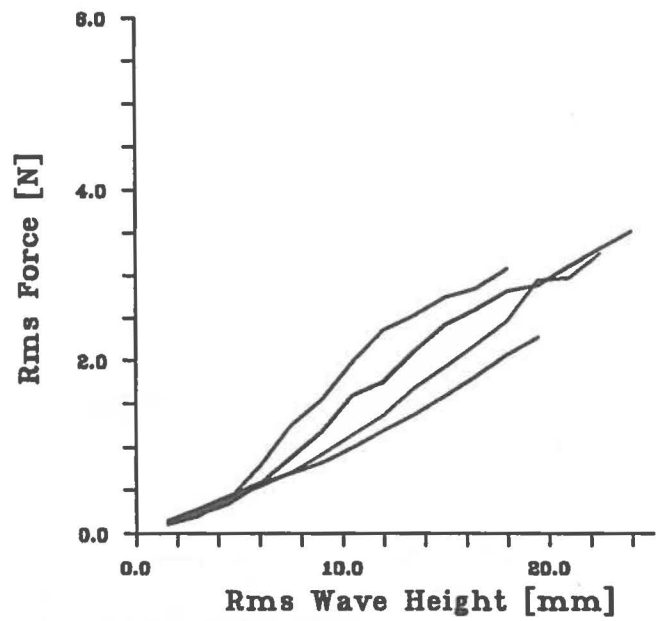


Figure 5.3: Heave and surge rms forces in Pierson-Moskowitz waves

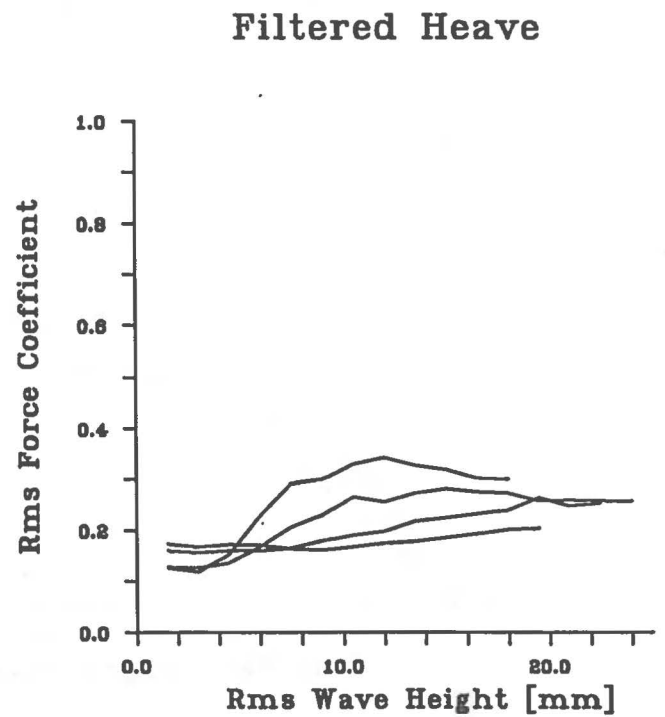
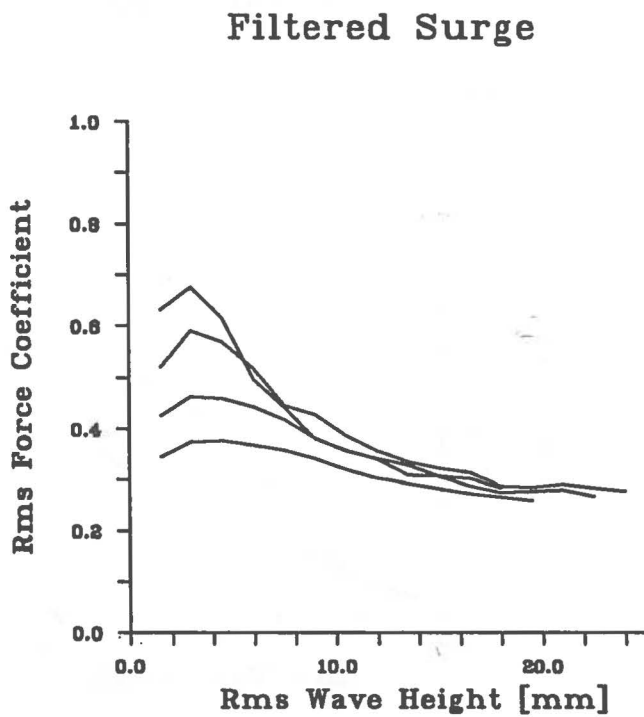
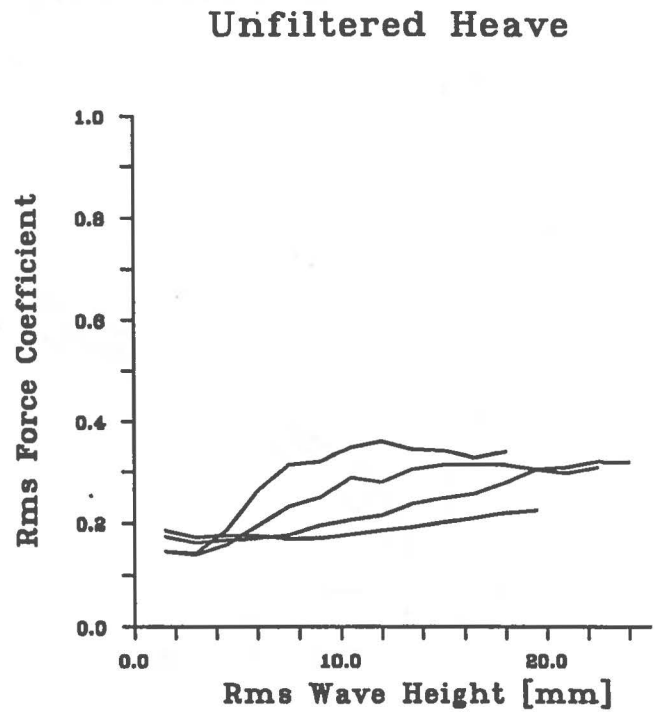
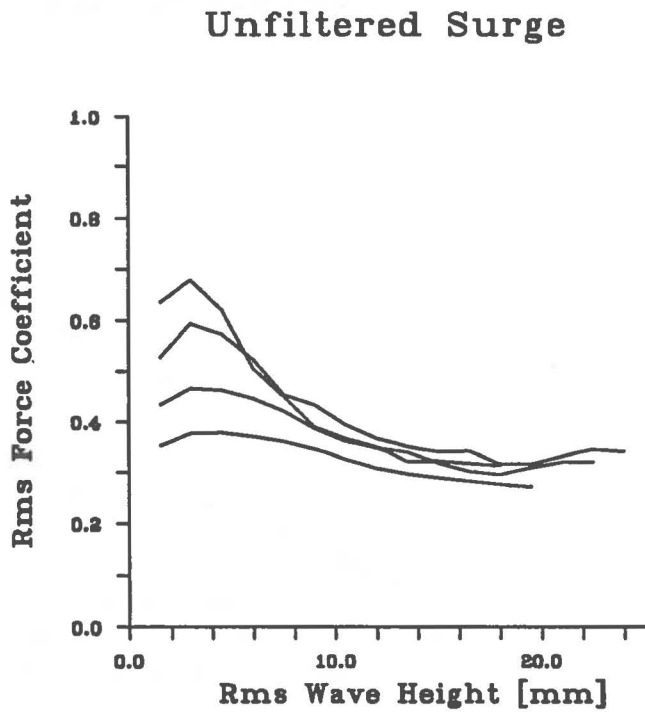


Figure 5.4: Heave and surge rms force coefficients in Pierson-Moskowitz waves

These are the wave heights at which the down force due to capsize plays a major part in the forces. The discrepancy may be in part due to the inclusion of the mean down force in the rms calculations.

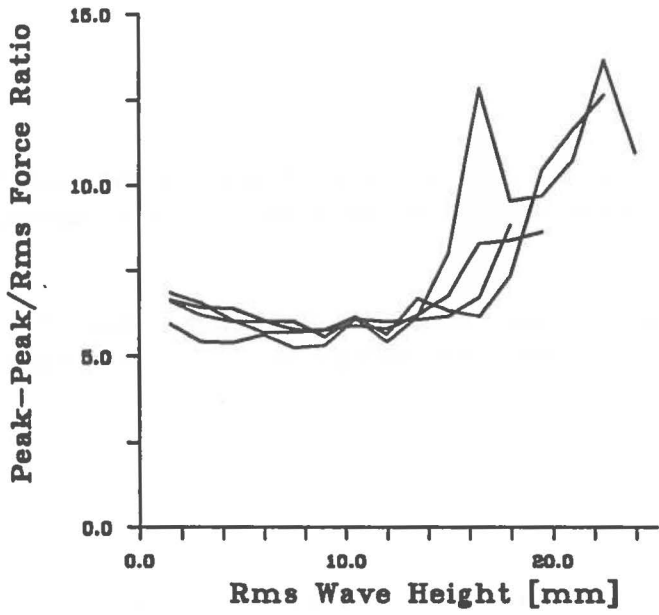
5.1.5 Peak-peak/rms force ratios

The peak-peak/rms force ratios that can be expected over any given period is dependent on the length of time over which the measurements take place (see also section 3.2.5). Figure 5.5 shows the derived heave and surge peak-peak/rms force ratios in these tests. These can then be compared with the measured peak-peak/rms wave height ratio measurements and with theoretical predictions for the given sampling time (51.2 seconds) and the wave periods (see section ()).

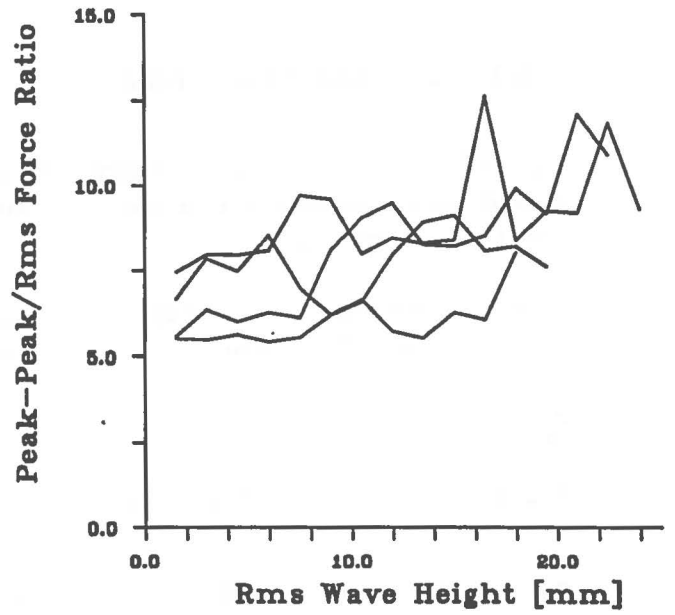
The graphs show good agreement with the measured peak-peak/rms wave height ratios in figure 2.2 in surge up to the point of snatching. In heave the effect of down force due to capsize produces a much wider spread of ratios as both the rms and peak-peak forces are affected.

Above the wave heights that cause the wires to go slack the snatch peak-peak/rms force ratios rise very sharply. The magnitude of the snatch ratios show how forces that would normally occur extremely infrequently can appear with unfortunate regularity.

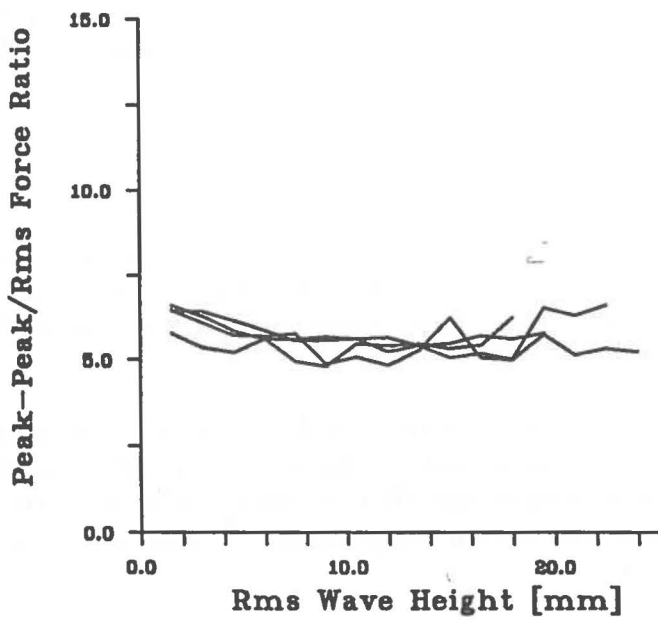
Unfiltered Surge



Unfiltered Heave



Filtered Surge



Filtered Heave

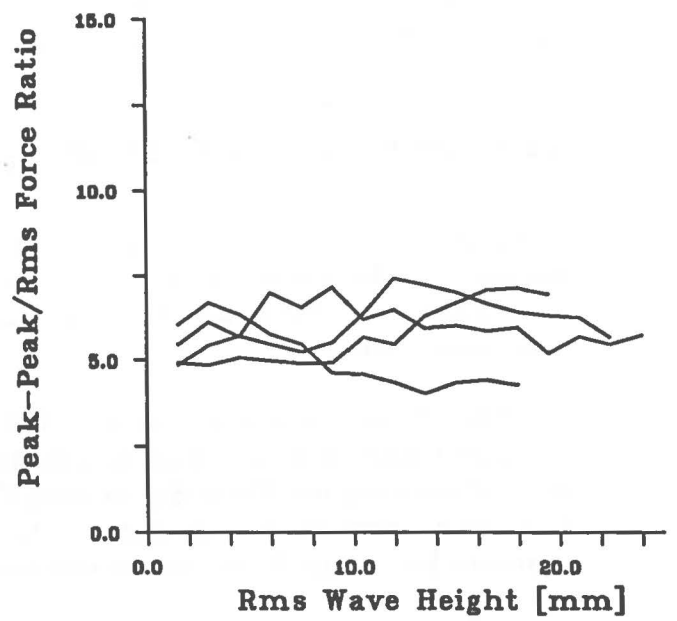


Figure 5.5: Heave and surge peak-peak/rms force ratios in Pierson-Moskowitz waves

5.2 Freak wave results

The wave records from chapter 4 are used to derive equivalent heave and surge results for freak waves in this section.

5.2.1 Rms and peak forces

Figure 5.6 shows the heave and surge rms forces derived from the Pierson-Moskowitz tests and the peak forces measured in a freak wave. The rms forces are included to give an idea of relative magnitude (see also section 4.2.2).

The dominant features in the graphs are the heave and surge peaks that are caused by snatching in the fore wire. When these forces are excluded by filtering, the resulting underlying forces are much smaller by comparison.

5.2.2 Minimum and maximum forces

Separating the positive and negative peaks reveals the asymmetry in these forces. Figure 5.7 shows the minimum and maximum forces in heave and surge. The horizontal straight line is the static force in calm water. In surge it is zero while in heave it is the buoyancy force.

The maximum force in heave and minimum force in surge is due to the large snatch forces in fore while maximum force in surge is due to the snatch force in aft. The minimum heave forces cannot show snatch forces but they can be affected by oscillations in aft that are induced by snatching in fore (see section 3.1.2). This results in a discrepancy between the unfiltered and filtered forces.

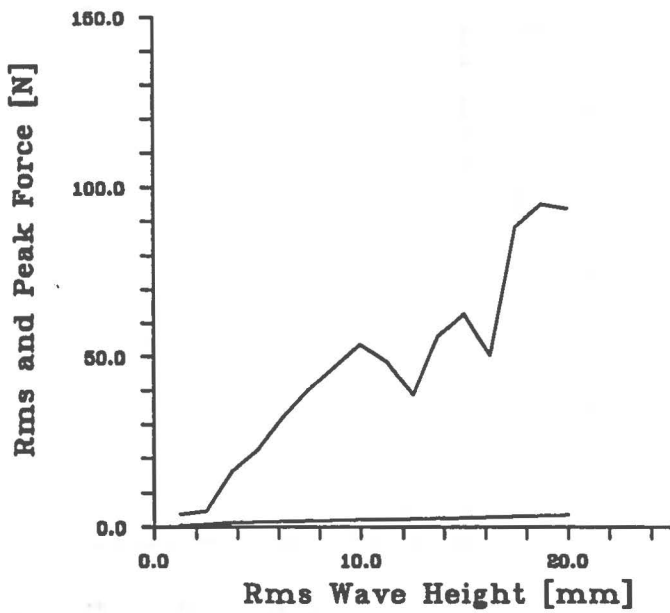
When the heave minimum force goes to zero it is an indication that both fore and aft wires have gone slack. The filtered version of the forces shows that even a freak wave has difficulty sinking the duck.

5.2.3 Peak-peak/rms force ratio

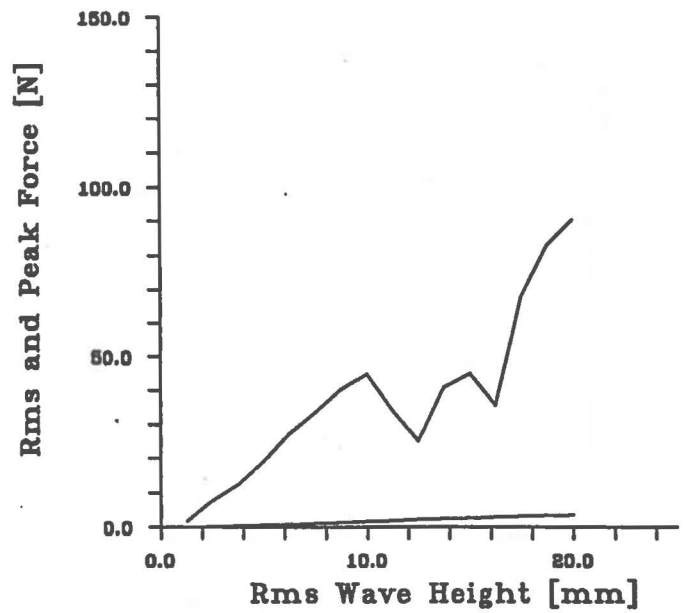
The peak-peak/rms force ratios in heave and surge are shown in figure 5.8. Note that rms forces are derived from the Pierson-Moskowitz results from section 5.1 (see also section 4.2.2). The horizontal straight line is the theoretical peak-peak/rms wave height ratio based on the linear sum of the component waves.

The filtered forces with snatching excluded show a strong downward trend of ratio with increasing rms wave height. With snatching included the ratio can far exceed the theoretical ratio. Without the effect of snatching and the ability to cause the wave crests to coincide to produce a freak wave, these ratios would normally be expected with tank runs that last for many millions of times the present estimates for the age of the universe (see section ()).

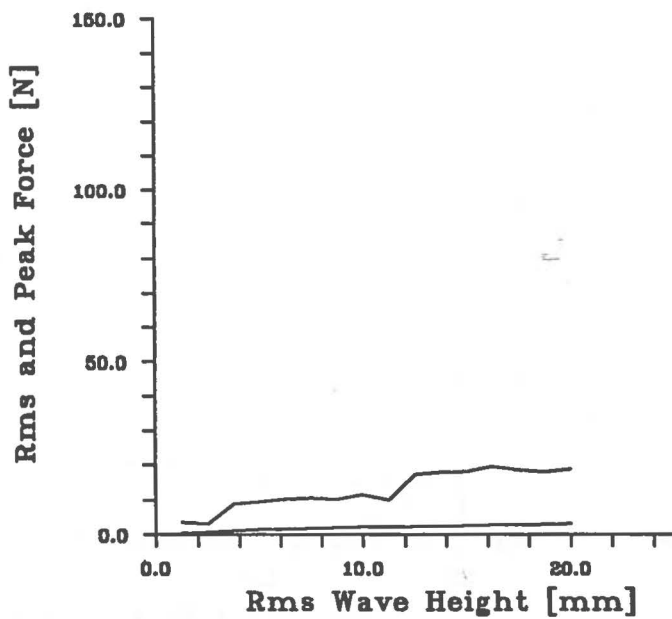
Unfiltered Surge



Unfiltered Heave



Filtered Surge



Filtered Heave

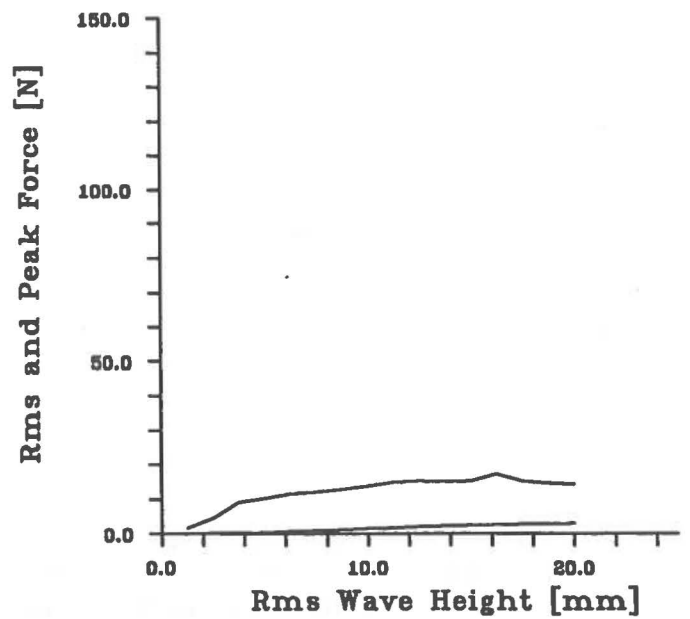
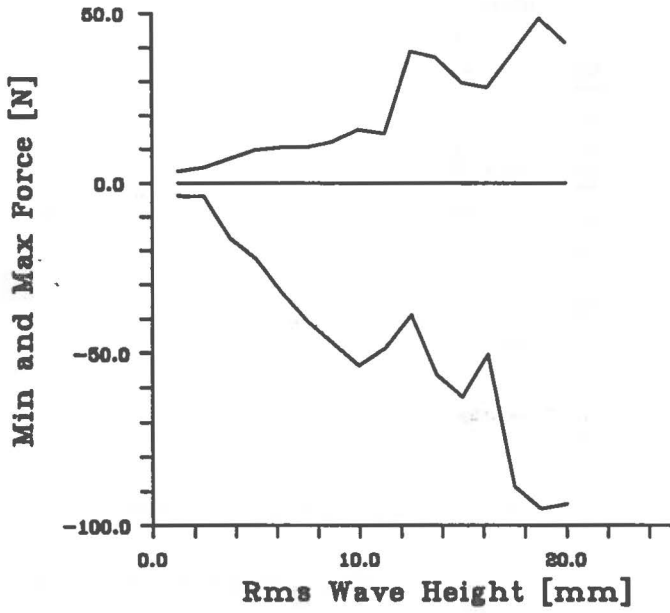
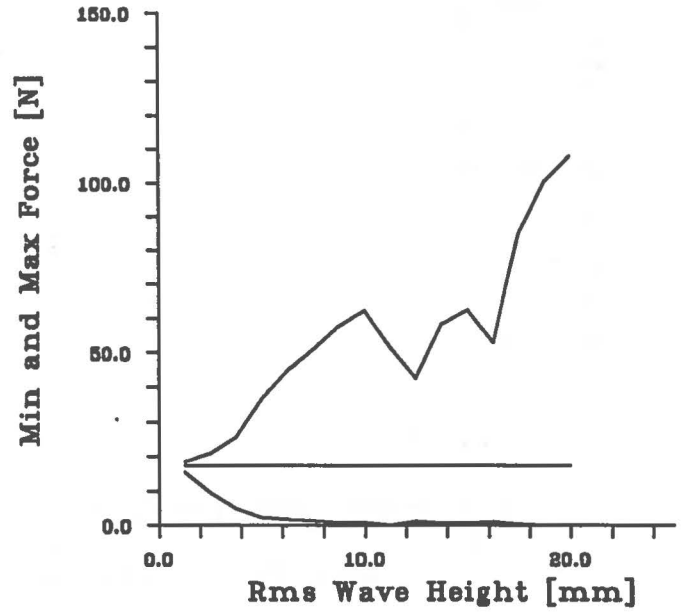


Figure 5.6: Heave and surge rms and peak forces in freak waves

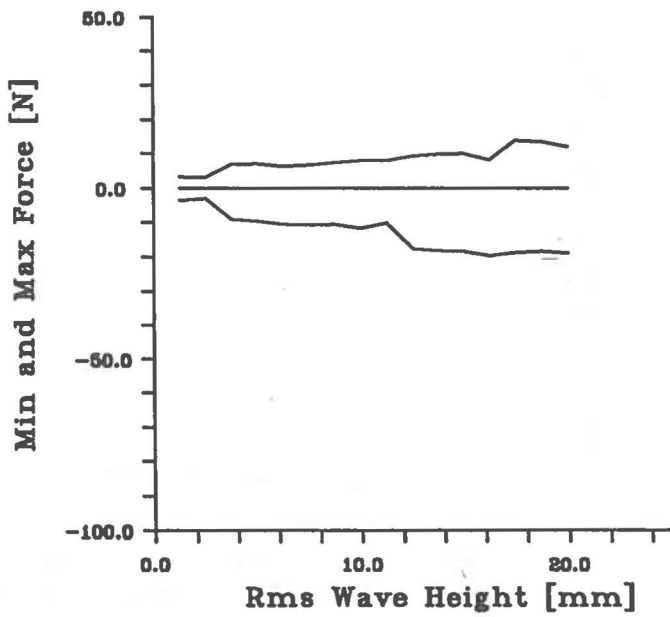
Unfiltered Surge



Unfiltered Heave



Filtered Surge



Filtered Heave

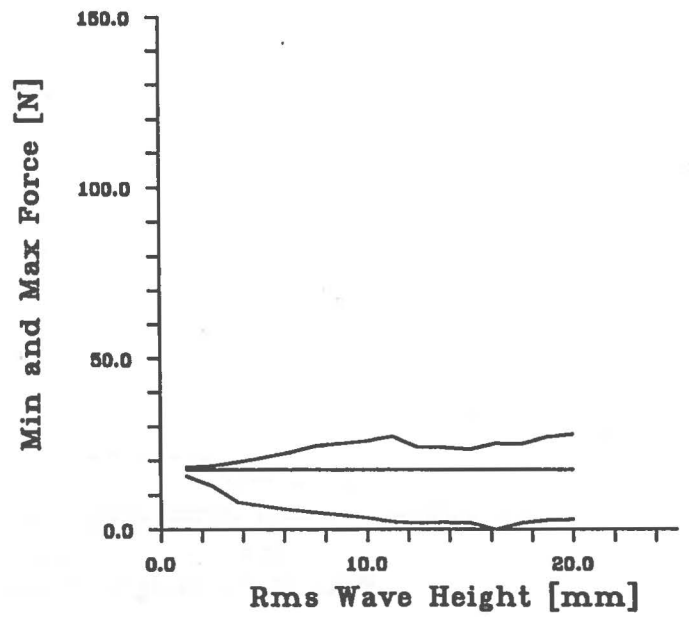
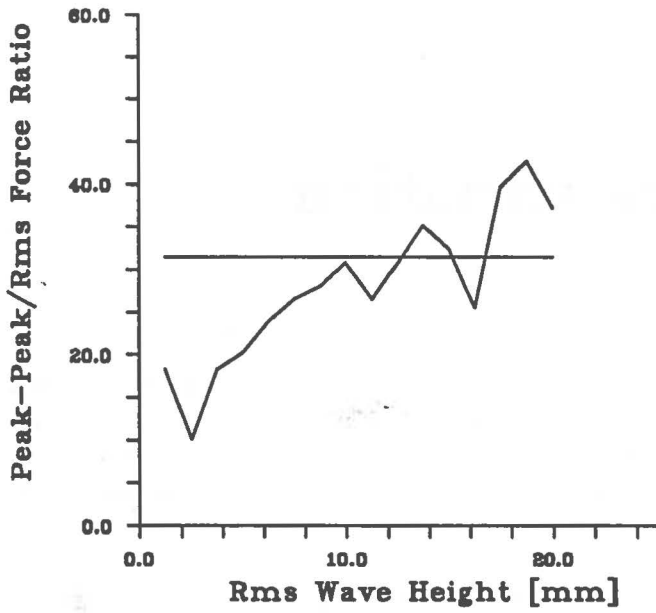
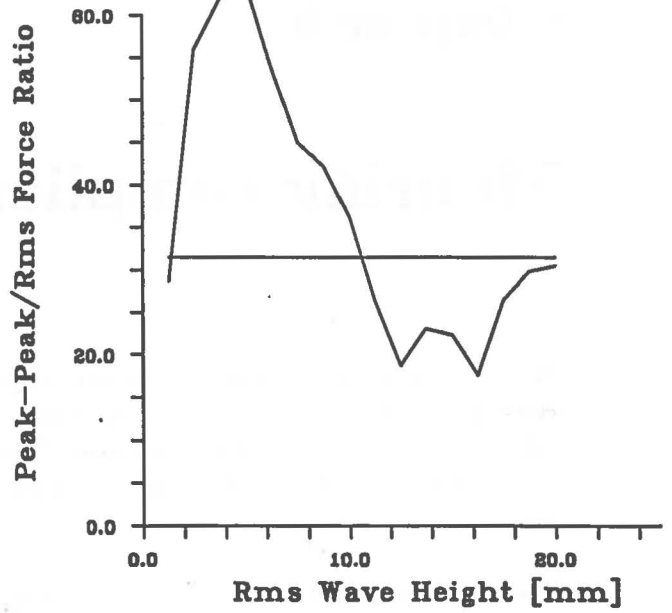


Figure 5.7: Heave and surge minimum and maximum forces in freak waves

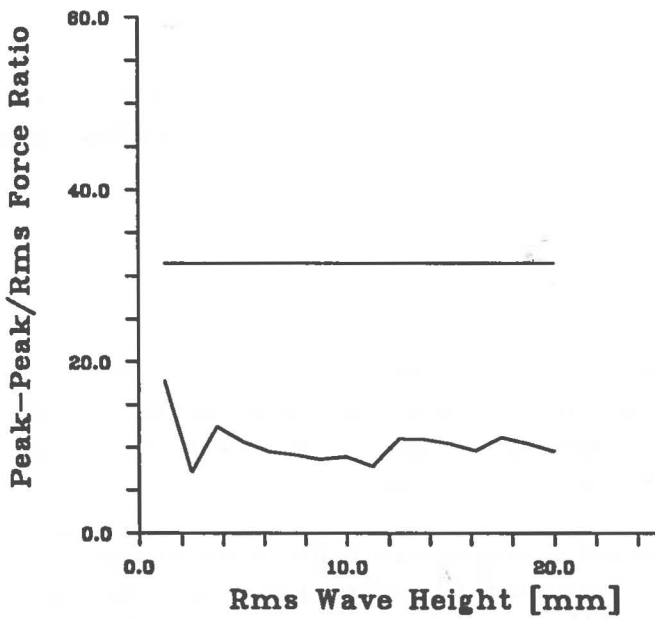
Unfiltered Surge



Unfiltered Heave



Filtered Surge



Filtered Heave

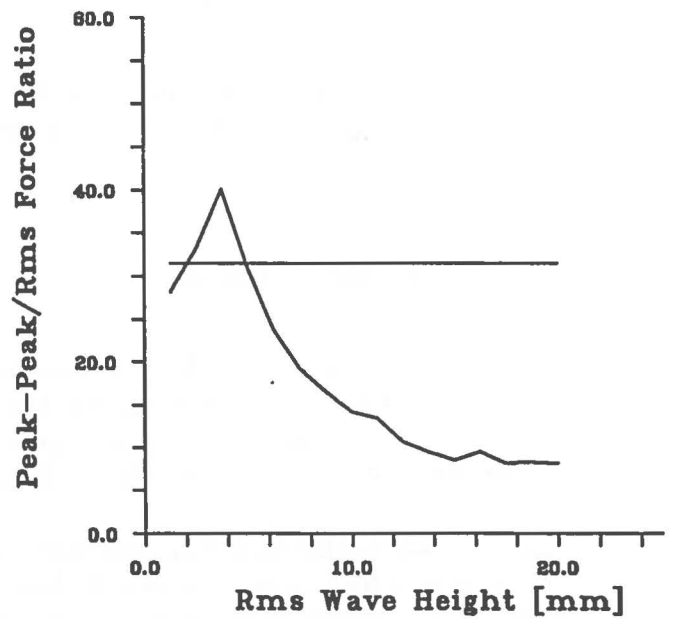


Figure 5.8: Heave and surge peak-peak/rms force ratios in freak waves

Chapter 6

Mooring compliance variation

The compliance in the mooring system plays a major part in the forces on tension leg devices. At the extreme where the compliance tends to zero the wave force acting on the duck reaches a limiting finite value. Forces on the moorings resulting from snatching, on the other hand, will tend to infinity. It is the kinetic energy built up during the slack period that needs to be absorbed by the moorings which tends to a finite value.

The intention in this chapter is to investigate the effect of mooring compliance variation. The motivation behind it is to investigate the possibility of adding compliance into the moorings in series with the power take-off system thus reducing the worst of the snatch forces. The compliance should be large enough to reduce the forces to acceptable levels but without resulting in a significant loss in efficiency. At the extreme where the compliance is infinite the forces will tend to zero but so will the power output.

6.1 Effect of compliance on force records

The effect of mooring compliance variation is best illustrated using the force records directly. These show the change in maximum force and the change in the resonant frequency of the oscillations due to snatching.

6.1.1 Fore force records

Figure 6.1 shows a series of force records measured in a freak wave on a duck with varying mooring compliance. The compliance in the top trace is due partly to the wire but mostly to the load cell. It is in fact the standard test set up as in previous chapters. The compliance in subsequent traces is due to the addition of one, two and three coil springs in series respectively.

The top trace has the large force and high oscillation frequency seen in chapter 4. In subsequent traces the maximum force is reduced and the frequency of the snatch oscillations is also lower. The addition of the first spring has reduced the force to about half the standard case but subsequent additions have much less effect. Even in the most compliant case tested the maximum force is still nearly four times the buoyancy force.

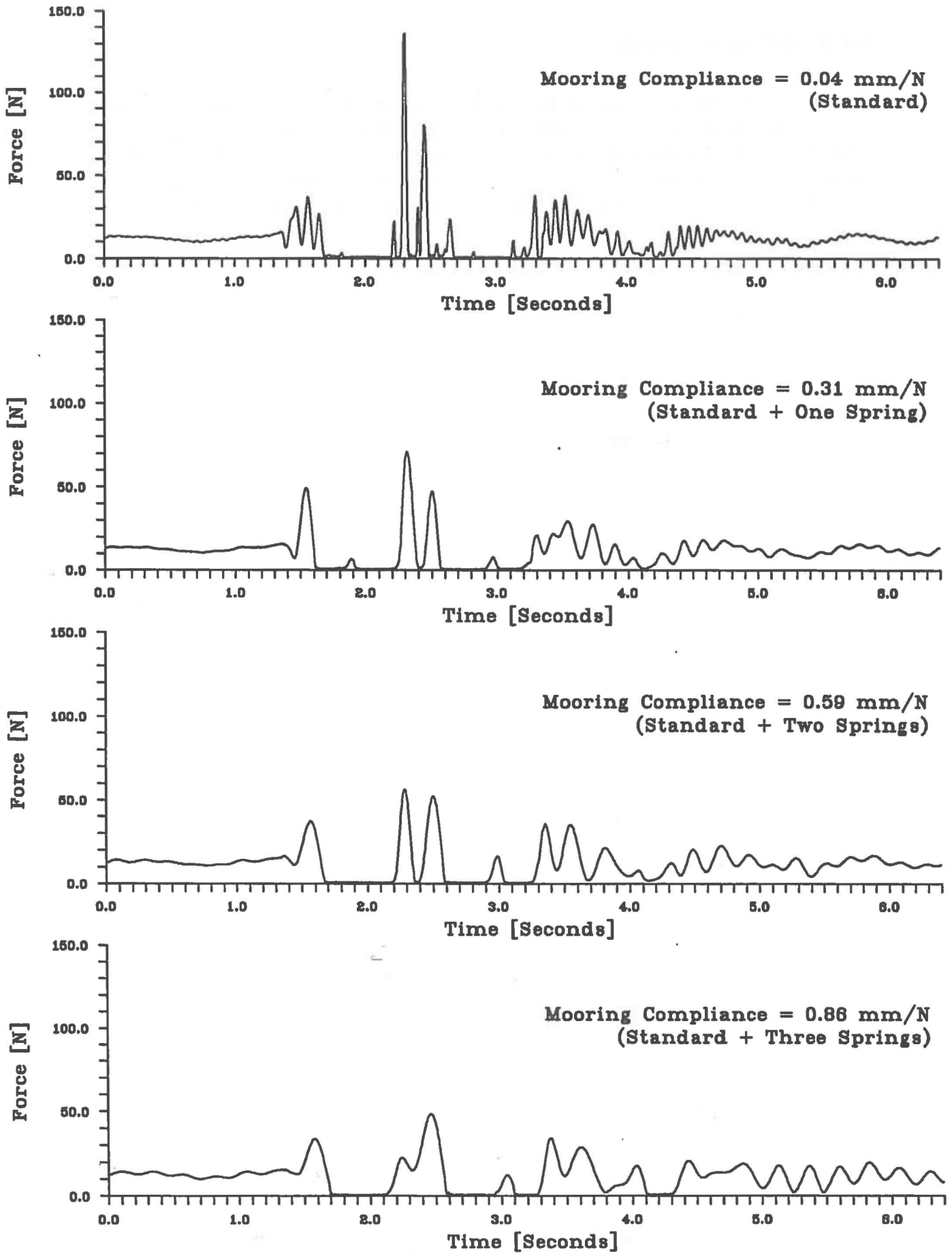


Figure 6.1: Fore force records in a freak wave varying mooring compliance

6.1.2 Aft force records

The aft force records are similar to the fore force records. Figure 6.2 shows the aft forces measured in the same test conditions as in section 6.1.1. Here The frequency of the snatch oscillations does decrease with increasing compliance but the maximum forces are hardly affected. The compliance in the load cell in aft is enough to achieve what the addition of the first coil spring achieves in the fore wire. The addition of further springs does reduce the force but not significantly.

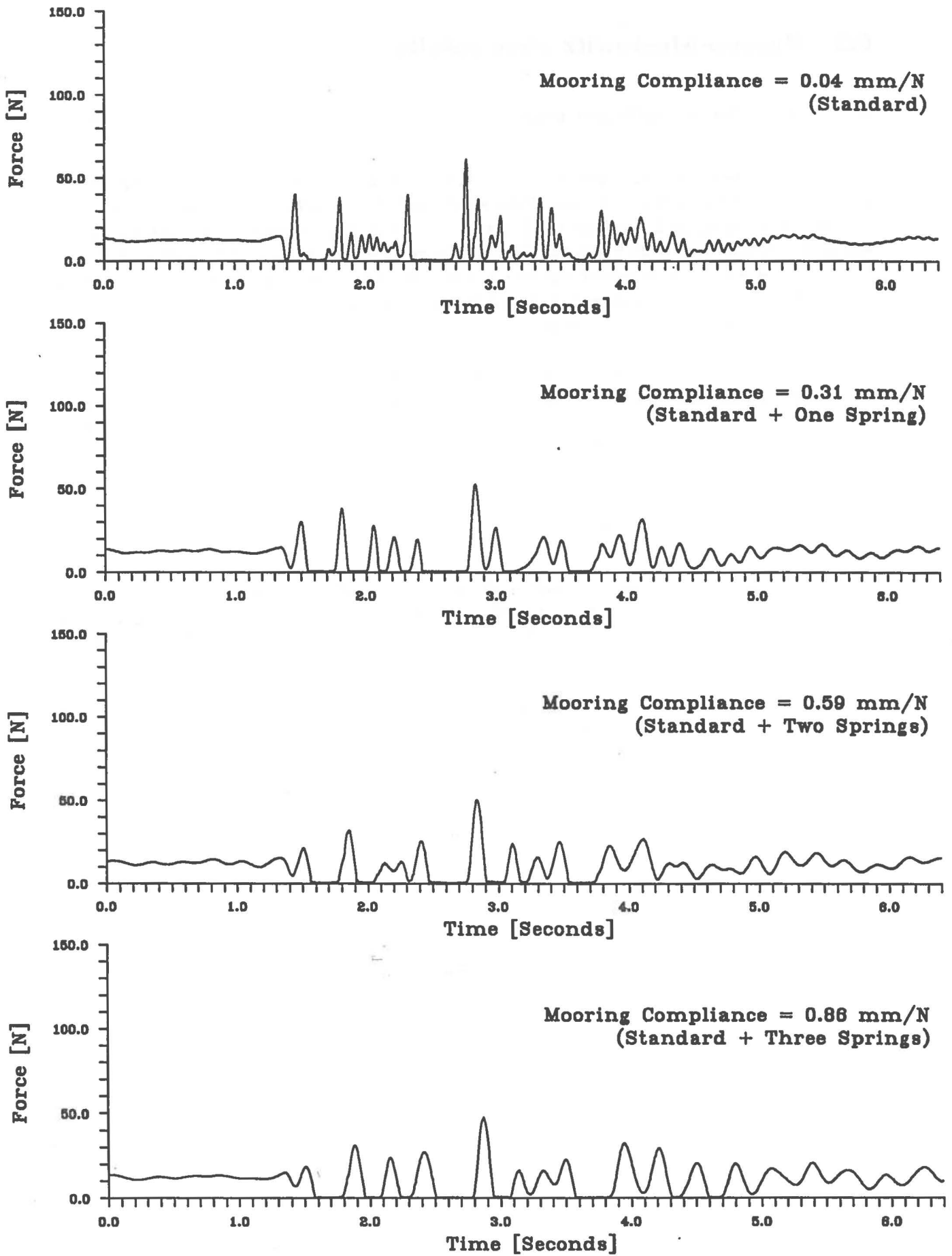


Figure 6.2: Aft force records in a freak wave varying mooring compliance

6.2 Pierson-Moskowitz wave results

6.2.1 Rms force coefficient ratios

The rms force coefficients are presented for each of the compliance tests as a ratio to the corresponding coefficients in the standard test case. Figure 6.3 shows these ratios (the coefficients in the standard case are shown in figure 3.10). Rms coefficient ratios are in fact the same as rms ratios in these tests as the duck diameter and duck width are the same as in the standard case. The solid lines in the graphs are the ratios using the unfiltered versions of the force records in both the compliance test cases and the standard case while the dashed lines are the ratios using the corresponding filtered versions. The horizontal solid straight line represents a ratio of one to one.

In all the graphs the rms forces increase with compliance. There is also a deviation between the unfiltered and filtered versions of the ratios with increasing compliance. The closer the resonant frequency in the mooring gets to the spectrum wave frequencies, the more these oscillations are excited. This increases the unfiltered versions of the rms forces.

6.2.2 Peak-peak/rms force ratios

The peak-peak/rms force ratios are shown in figure 6.4. Compare these with the equivalent ratios in the standard test case (see figure 3.11) and the equivalent wave height ratios (see figure 2.2). The solid lines are the ratios using the unfiltered versions of the force records while the dashed lines are the ratios using the corresponding filtered versions.

In all the tests the oscillations in the moorings increase the ratios compared to the underlying ratios. These underlying ratios are broadly similar in magnitude to the corresponding wave height ratios.

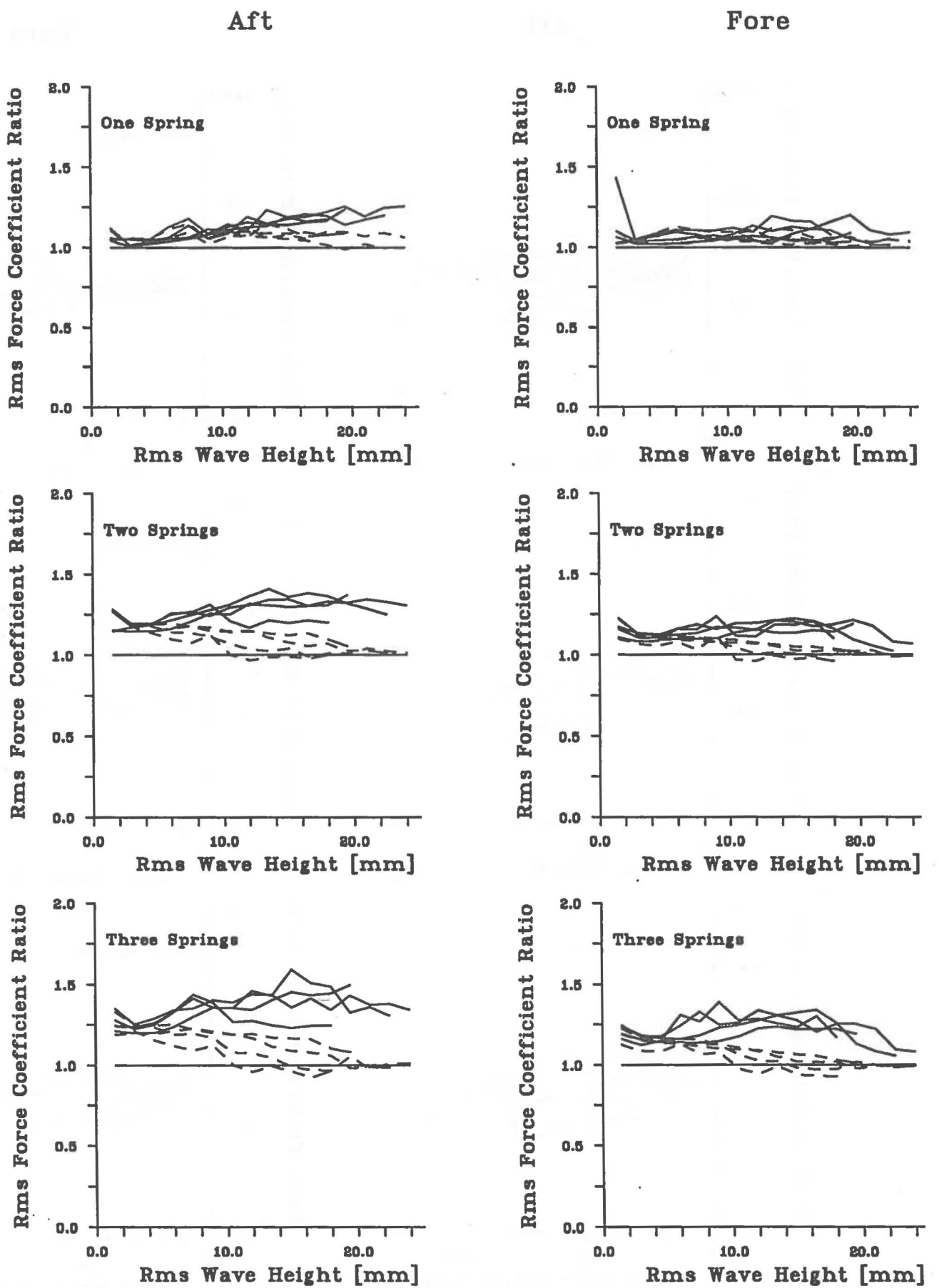


Figure 6.3: Rms force coefficient ratios in Pierson-Moskowitz waves varying mooring compliance

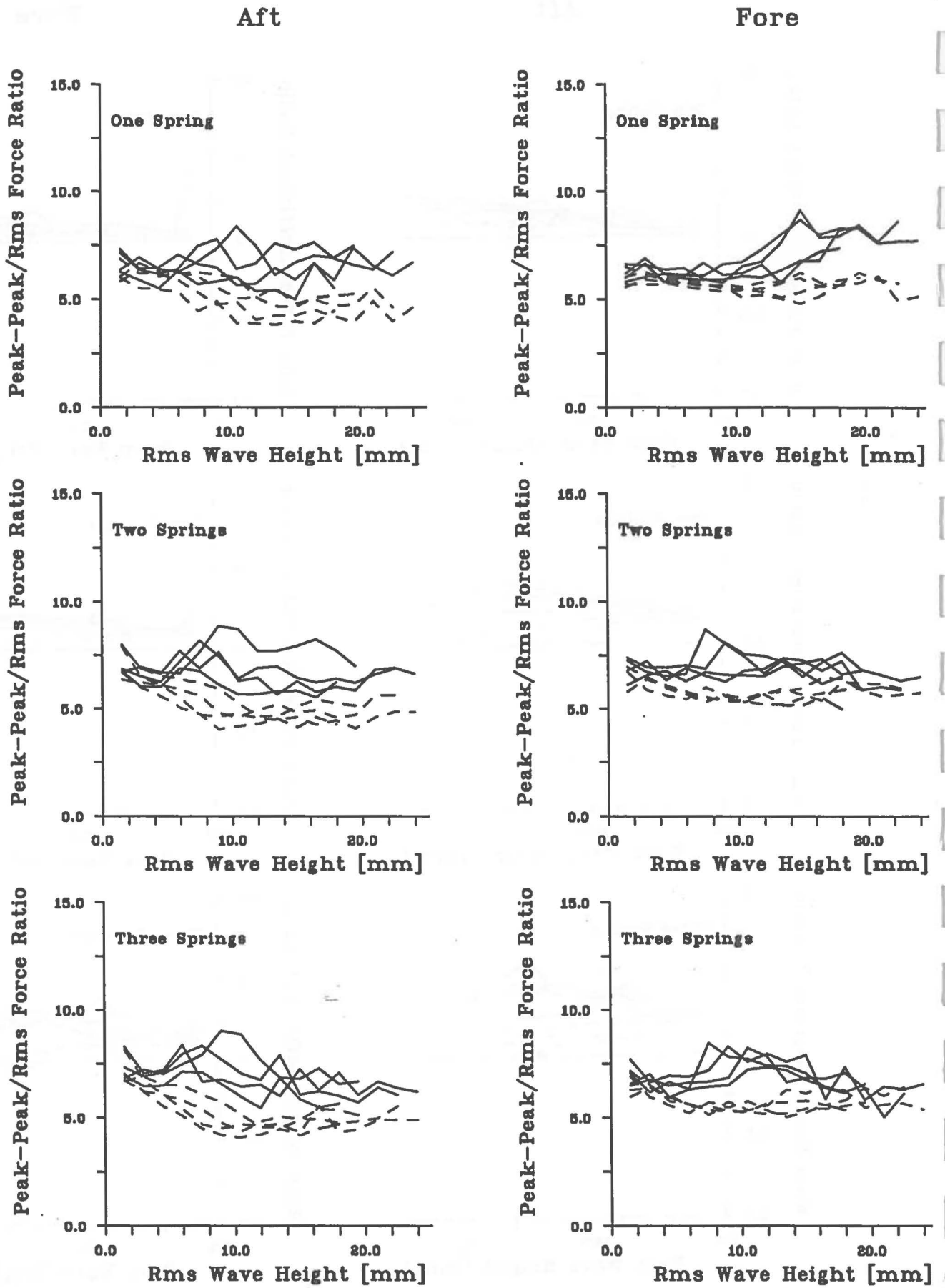


Figure 6.4: Peak-peak/rms force ratios in Pierson-Moskowitz waves varying mooring compliance

6.3 Freak wave results

6.3.1 Peak-peak/rms force ratios

Figure 6.5 shows the peak-peak/rms force ratios for each of the compliance tests. These should be compared with the equivalent ratios in the standard test case (see figure 4.11). The solid lines are the ratios using the unfiltered versions of the force records while the dashed lines are the ratios using the corresponding filtered versions. The horizontal solid straight line is the theoretical peak-peak/rms wave height ratio based on the linear sum of the component waves. Note that the rms forces used to calculate the ratios are the rms forces in an equivalent wave with randomised phases. They are derived from the Pierson-Moskowitz runs in each of the test cases (see section 4.2.2).

While in all the tests snatching is present and the unfiltered forces are much larger than the corresponding filtered ones, they are small compared to the equivalent forces in the standard test case. The filtered versions of the force ratios are, on the other hand, broadly similar in magnitude to their equivalent ratios in the standard case.

6.3.2 Snatch energy and force variation

Figure 6.6 shows the variation in snatch energy and force with increasing compliance. The four data points are derived from the corresponding freak wave records shown in figures 6.1 and 6.2. The energies shown are the maximum energies absorbed during snatching. These are stored as potential energy in stretch in the moorings. They are derived from the maximum snatch force and the compliance in each test case. The maximum snatch forces are also shown. The solid lines in the energy graphs show the potential energy stored in the moorings in calm water as a result of the tension due to buoyancy. These tension forces are also shown as solid lines in the force graphs.

The kinetic energy built up in the duck just prior to snatching appears to depend on the compliance. Wave forces acting on the duck during the travel of the mooring from the point where tension is restored to the point of maximum force can also add to the energy that needs to be absorbed. The graphs show that for very stiff moorings, the kinetic energy built up in fore is significant while in aft this energy is very small by comparison. It seems that the wires in aft have only just gone slack.

The graphs seem to suggest that as the compliance approaches zero the snatch forces in aft approach a finite value. This can only be the case if there is no kinetic energy to be absorbed in aft. If there is any energy at all then the forces will rise sharply as they do in fore but at much lower values of compliance.

Aft

Fore

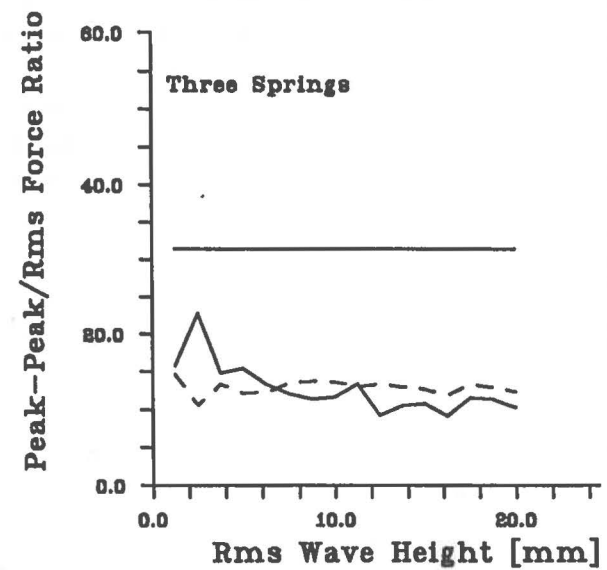
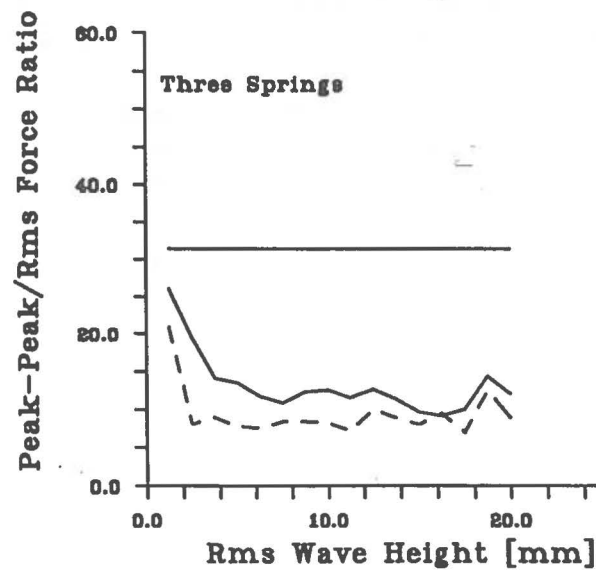
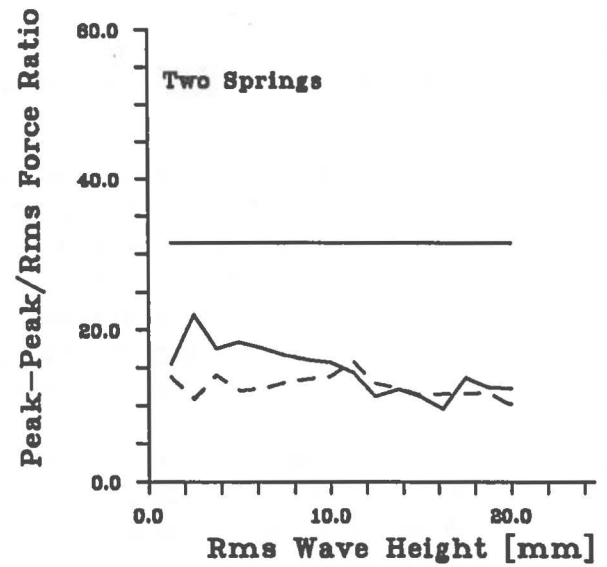
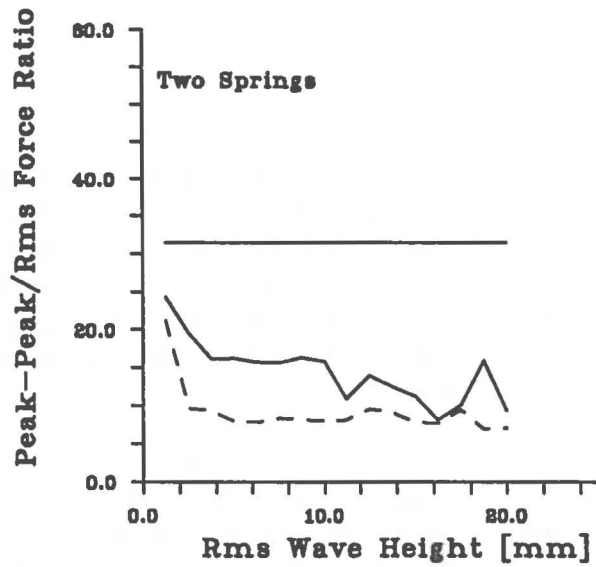
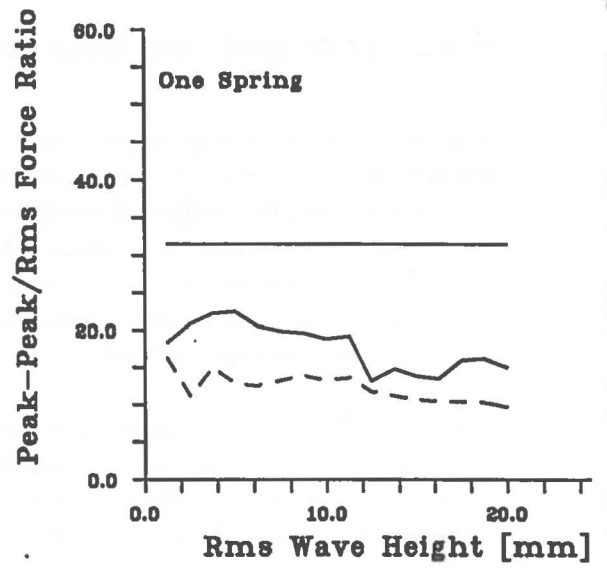
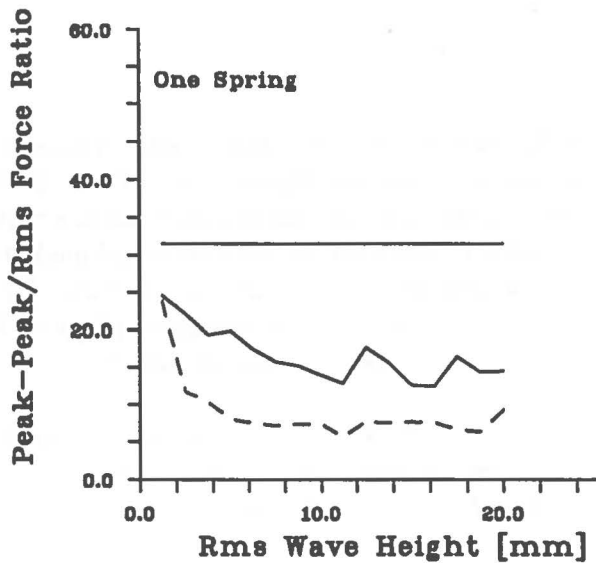


Figure 6.5: Peak-peak/rms force ratios in freak waves varying mooring compliance

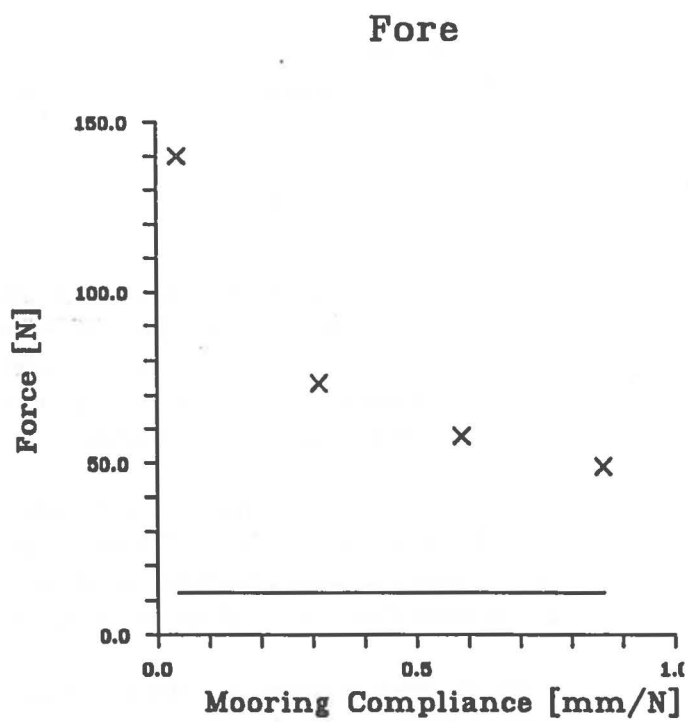
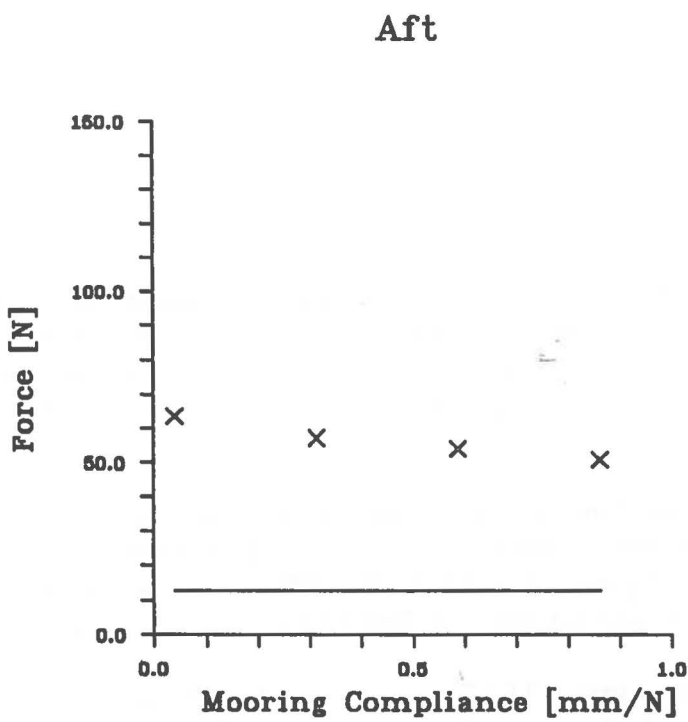
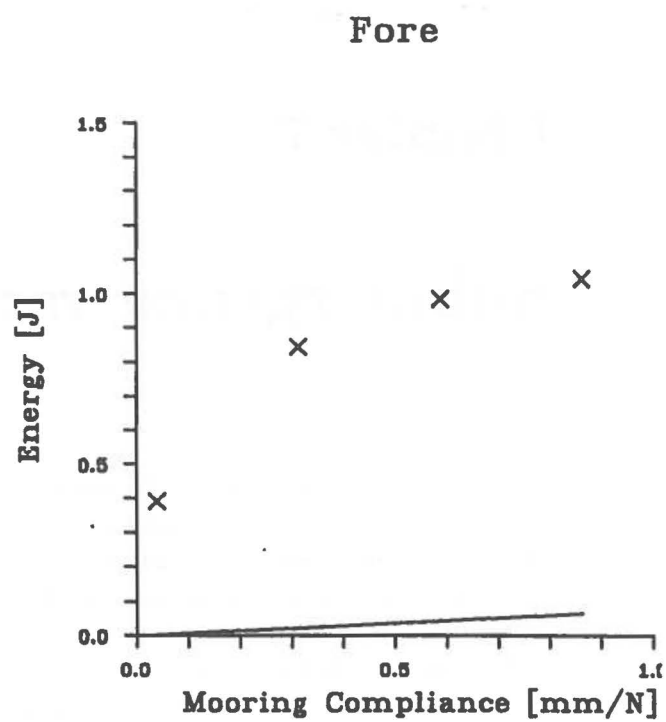
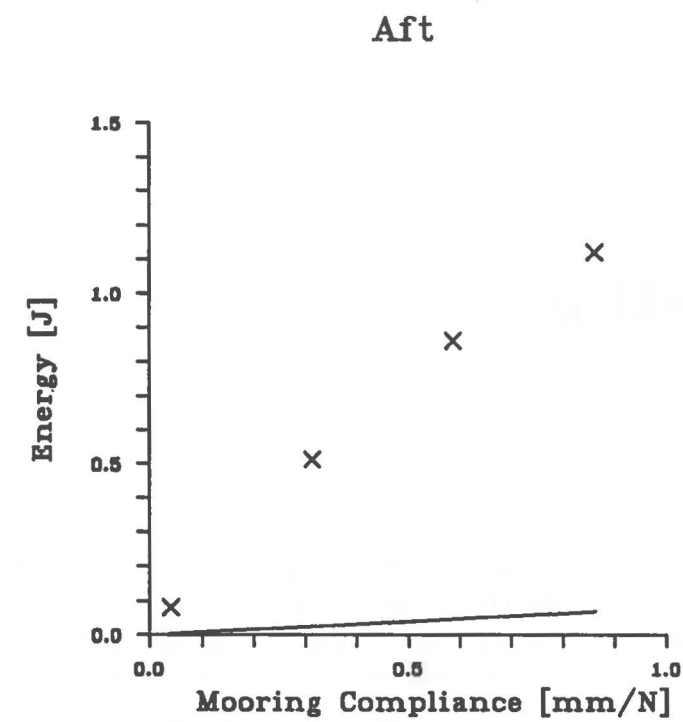


Figure 6.6: Snatch energy and force vs compliance in a freak wave

Chapter 7

Submergence variation

The largest wave motions can be found at the water surface. These motions decay with increasing water depth. Submerging a duck into relatively calmer conditions will therefore reduce the wave forces on it. This has the effect of reducing the likelihood of snatching. Submergence cannot be a complete solution to the snatching problem as it can occur frequently in the moderate conditions in which high efficiency is essential. It can however reduce the magnitude of the worst of the snatch forces by protecting the duck from snatching in the most severe wave conditions. It is assumed here that a mechanism would be included in the design to allow very large movement. The mechanism need only operate very slowly with changing wave conditions and will therefore need very little power.

7.1 Effect of submergence on the force records

Submerging the duck changes the appearance of the force records. The wires never go slack and the effect of snatching disappears even in the freak wave.

7.1.1 Fore force records

Figure 7.1 shows a series of force records measured in a freak wave on a duck with varying degrees of submergence. In the top trace the duck is 10mm too high in the water. In the second trace the duck is in its standard position. It is the standard case from chapter 4. In the third and fourth traces the duck is submerged 135mm and 235mm below the standard position. Note that this is very deep for power take-off hydraulic rams to achieve.

The top trace is very similar to the standard case showing that in freak waves the duck is insensitive to small changes in hub depth. There is a reduction in force but similar reductions can be obtained with small changes to wave amplitude or phase (see figures 3.8 and 4.3). The difference in oscillations is also no more than can be observed in repeats of identical runs (see figure 4.2).

In the two bottom traces snatching is completely absent. The freak wave is violent enough to induce small oscillations but the wire never goes slack. In fact a significant proportion of the static tension is always maintained especially in the deeper test. The maximum forces on the duck are as high as three times the static force due to buoyancy in its normal operating position but not nearly as high as the snatch forces can be.

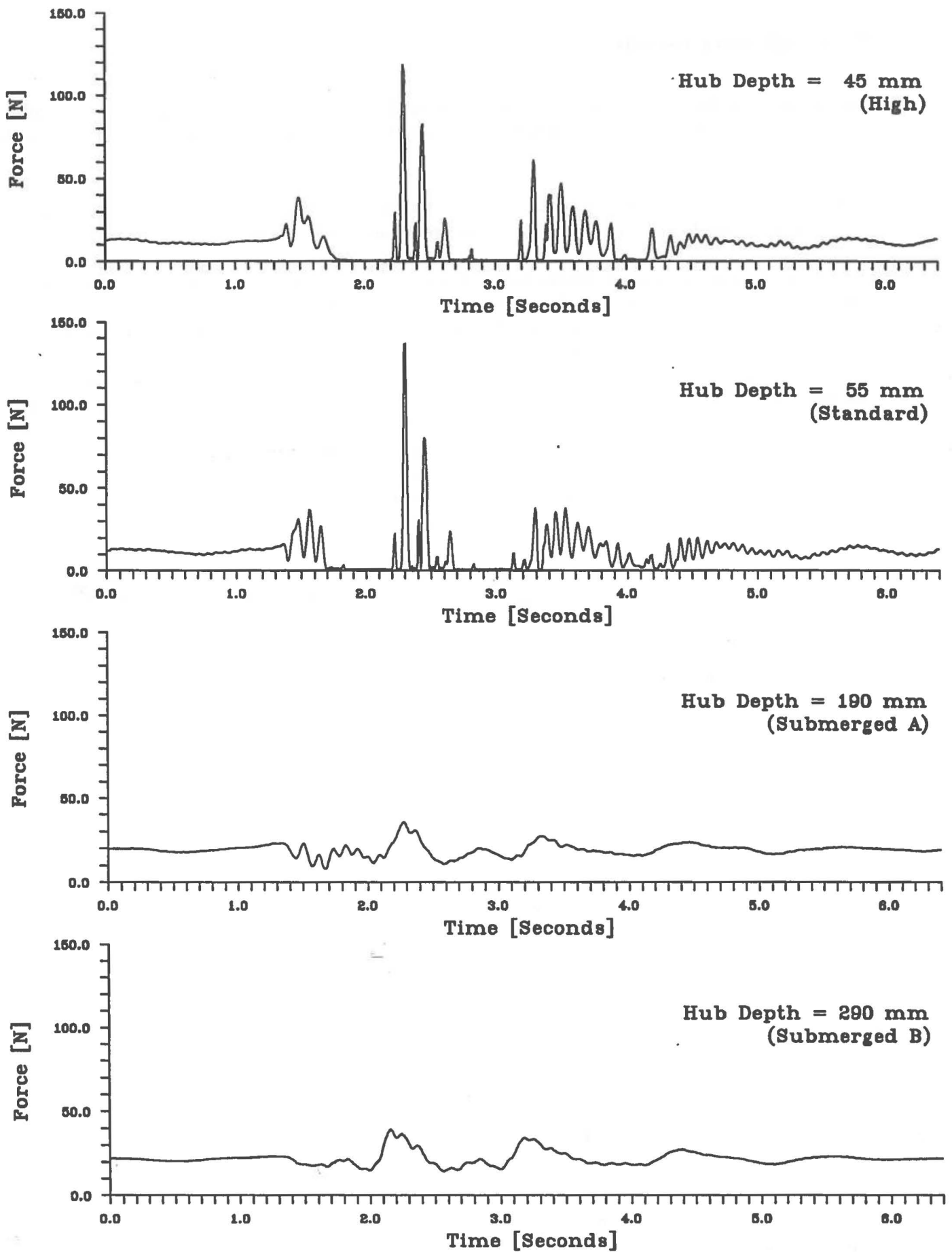


Figure 7.1: Fore force records in a freak wave varying submergence

7.1.2 Aft force records

The aft forces in freak waves have a similar trend to the fore forces except for the magnitude of the force when the duck is submerged. Figure 7.2 shows the aft forces in the same test conditions as in section 7.1.1.

The top trace is almost identical to the second trace apart from minor details in snatch oscillation. This indicates that the aft forces in freak waves are insensitive to small changes in hub depth.

As in fore, snatching disappears altogether in the two bottom traces although the traces do come very close to going slack in the first of these. In the standard duck position the largest forces are in fore but submerging the duck cause the larger forces to appear in aft. The direction of maximum force is dependent on the distribution of dynamic pressure of the water around the duck. In waves the greatest dynamic pressures can be found close to the surface. The duck acts as an obstacle to the wave thereby causing these dynamic pressures to be larger in front while behind the water is a little calmer. When the duck is in its normal position the largest dynamic pressures are acting on the surface that is on the side of the fore wire but when the duck is submerged the largest dynamic pressures are acting on the surface that is diagonally opposite the aft wire. This is probably the reason for the aft forces being greater than the fore forces when the duck is submerged. The effect breaks down in very long waves where the duck is no longer an effective obstacle.

The depth of submergence in the third trace appears to be the minimum that is needed to prevent snatching in the test freak wave for the given buoyancy. Putting it the other way around, the buoyancy in these tests is the minimum needed to prevent snatching for the depth of submergence in the third trace.

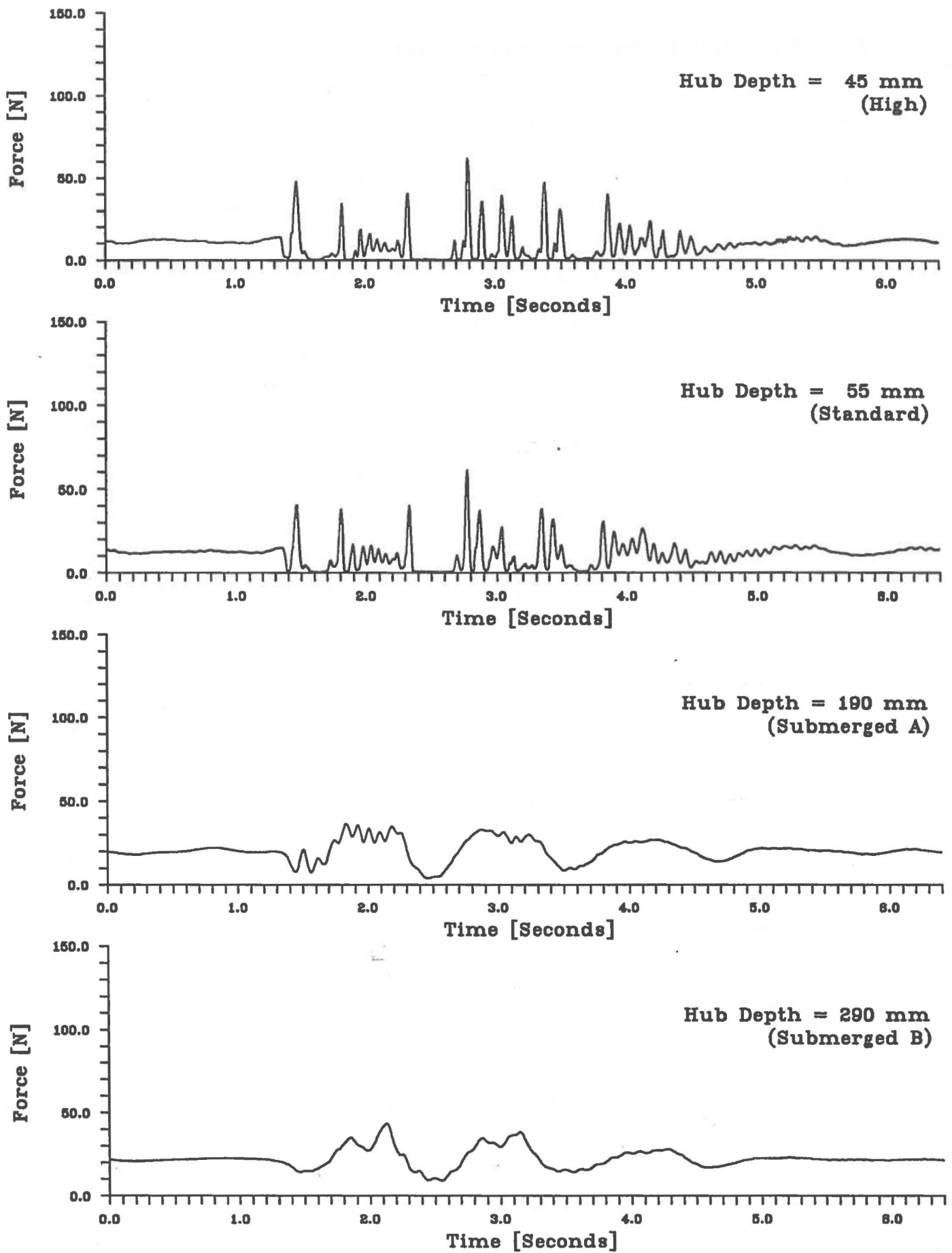


Figure 7.2: Aft forces in a freak wave varying submergence

7.2 Pierson-Moskowitz wave results

7.2.1 Minimum and maximum forces

Figure 7.3 shows the minimum and maximum forces on a duck with varying degrees of submergence. Compare these with the standard test case in figure 3.8. The horizontal line represents the static force due to buoyancy.

In the top traces the duck is 10mm too high in the water and the forces show a similar pattern to the standard test case. One small but important difference that does appear in the graphs is that the effect of down force due to capsize occurs at higher wave amplitudes (see section 3.2.2). The duck is visibly more stable in pitch when it is floating too high. The result is that larger waves are needed to capsize it.

When the duck is submerged the characteristic pattern in the force graphs disappears altogether. The positive and negative peaks are much more symmetric. The wires do not go slack and snatch peaks are absent. There is also no characteristic down step in force due to capsize. When the duck is submerged the beak of the duck is pointing upward all the time. Note also that the static force is higher as the duck is more buoyant when it is fully submerged.

7.2.2 Rms force coefficient ratios

The rms force coefficients are presented as a ratio of force coefficient in the test case to the standard case (see figure 3.10). The rms force coefficient ratios are in fact the same as rms force ratios since there is no change in duck diameter or duck width in these tests. Figure 7.4 shows ratios for each of the submergence tests. The solid lines are the ratios of coefficients using the unfiltered versions of the force records in both the submergence tests and the standard tests. The dashed lines are the coefficient ratios using the corresponding filtered versions of the records. The horizontal solid straight line is included to represent a reference ratio of one to one.

In all the graphs the filtered versions of the ratios follow the unfiltered version very closely except perhaps at the higher amplitudes in the submerged cases. It is only at these higher amplitudes that the contribution to rms force in the standard test case becomes significant. The contribution from snatch oscillation when the duck is too high in the water follows a similar pattern to that in standard test case. This explains the agreement between the unfiltered and filtered versions of the ratios in the top trace. When the duck is submerged there is no contribution from snatch oscillations and hence the discrepancy in the coefficient ratios. They are actually due to the difference between the unfiltered and filtered coefficients in the standard tests.

The most striking thing about these graphs is the increase in the aft rms forces in the first of the submergence tests (middle graphs). This phenomenon is due to the transfer of the larger forces from fore to aft when the duck is submerged (see section 7.1.2).

7.2.3 Peak-peak/rms force ratios

The peak-peak/rms force ratios for each of the submergence tests is shown in figure 7.5. These should be compared to the equivalent ratios in the standard test case (see figure 3.11) and the peak-peak/rms wave height ratios (see figure 2.2). The solid lines are the ratios using the unfiltered versions of the force records while the dashed lines use the corresponding filtered versions.

Aft

Fore

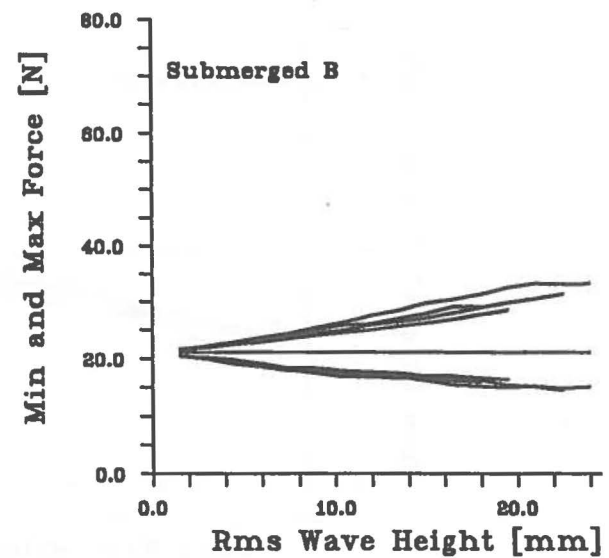
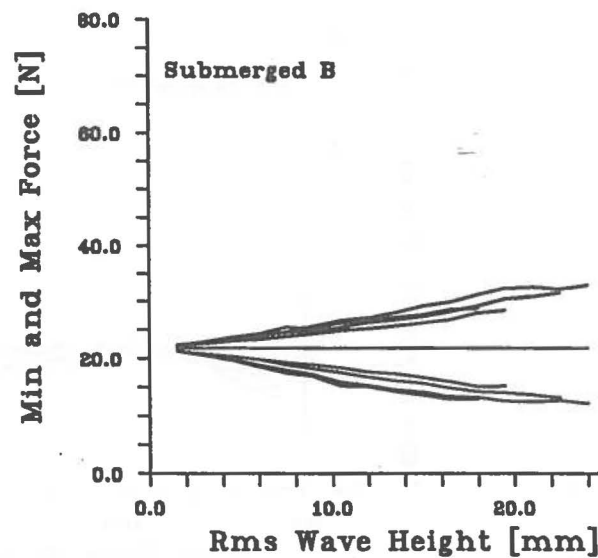
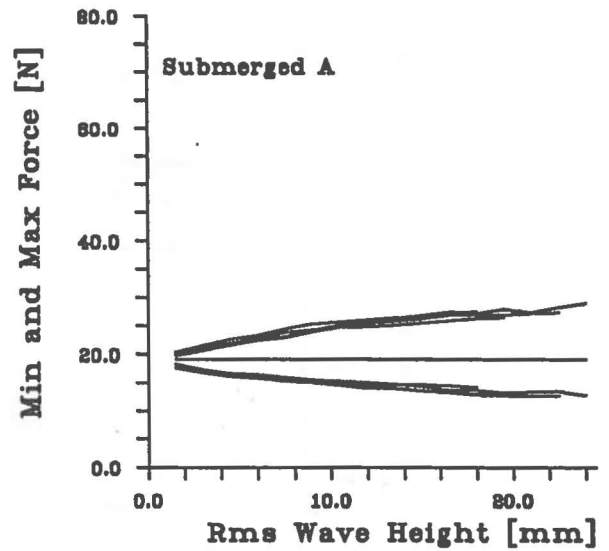
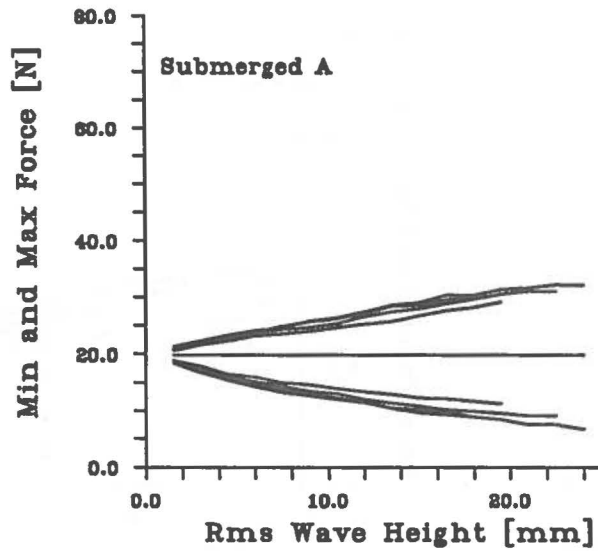
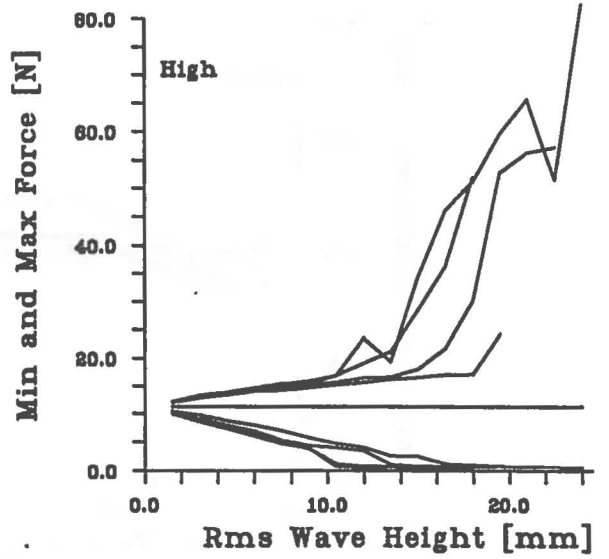
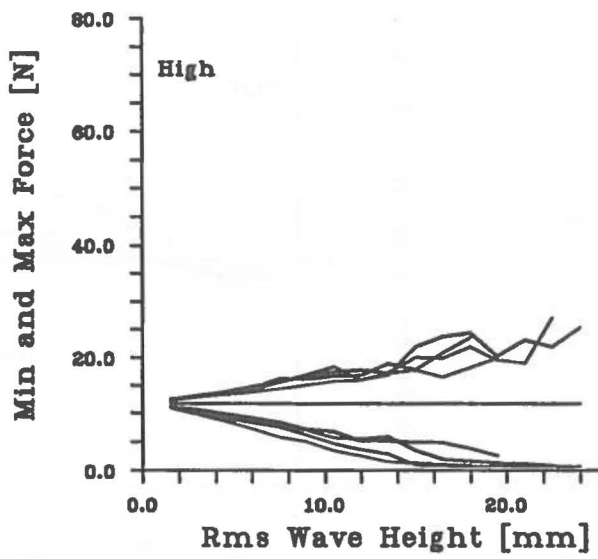


Figure 7.3: Minimum and maximum force in Pierson-Moskowitz waves varying submergence

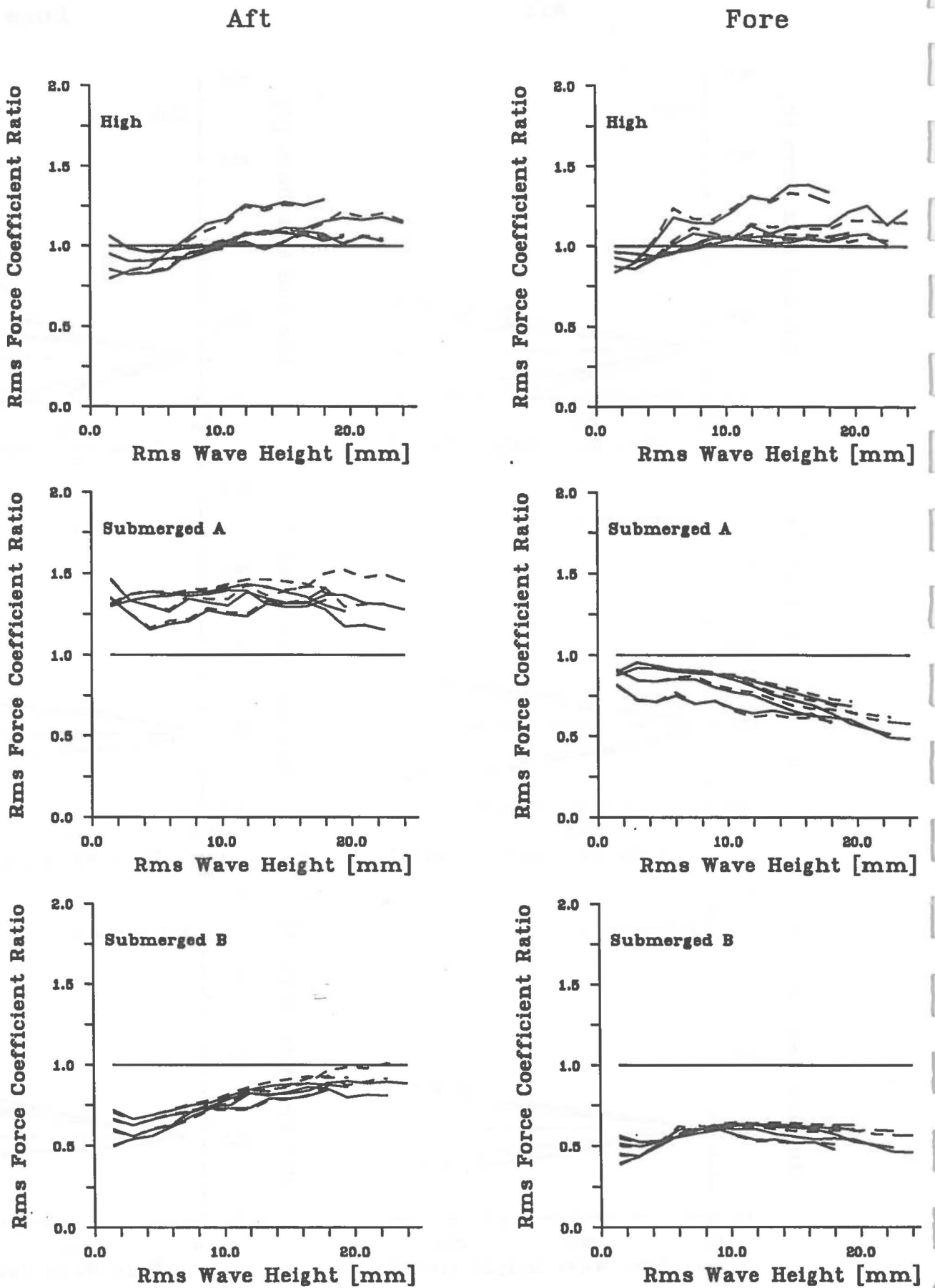


Figure 7.4: Rms force coefficient ratios in Pierson-Moskowitz waves varying submergence

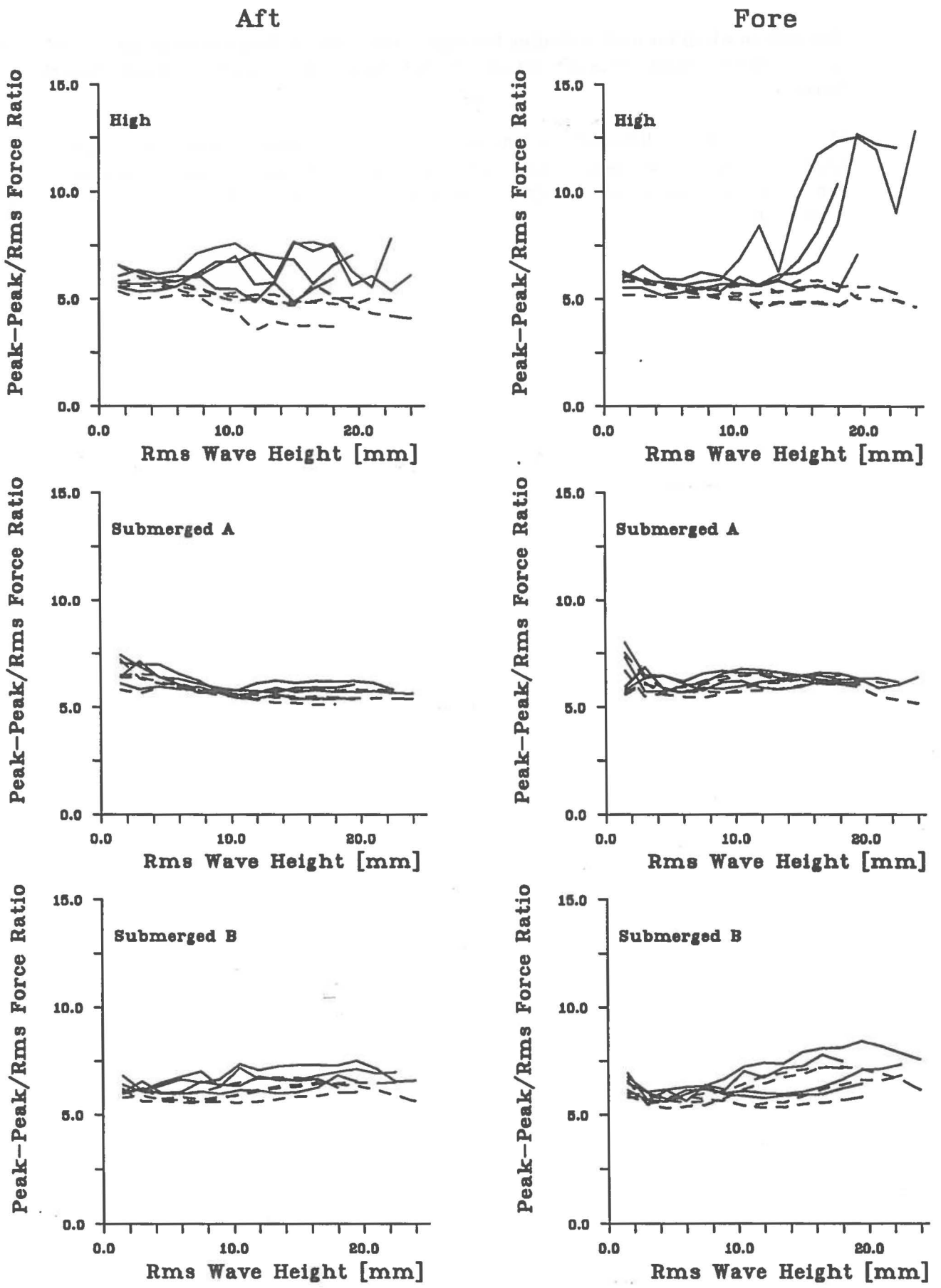


Figure 7.5: Peak-peak/rms force ratios in Pierson-Moskowitz waves varying submergence

The tests in which the duck is floating too high in the water produce similar results to the standard test case. Induced oscillations in aft and snatch peaks in fore make the forces larger than the underlying forces.

When the duck is submerged the induced oscillations are much smaller and oscillations that result from snatching are completely absent. The unfiltered and filtered versions of the graphs are therefore very close. In all the graphs the filtered versions of the ratios broadly agree with the equivalent wave height ratios.

7.3 Freak wave results

The amplitude sweeps in freak waves are missing for the case in which the duck is floating too high in the water. Results are therefore presented only for the submerged cases.

7.3.1 Minimum and maximum forces

Figure 7.6 shows the minimum and maximum forces for the two submergence cases. These should be compared with the equivalent minimum and maximum forces in the standard test case (see figure 4.10). The horizontal straight line represents the static force due to buoyancy. With no slack periods and snatch peaks the positive and negative peaks are much more symmetric than in the standard test case.

7.3.2 Peak-peak/rms force ratios

The peak-peak/rms force ratios in a freak wave are shown in figure 7.7. Compare these with the equivalent ratios in the standard test case (see figure 4.11). The solid lines are the ratio using the unfiltered versions of the force records while the dashed lines are the ratios using the corresponding filtered versions. The horizontal solid straight line is also included to represent the theoretical peak-peak/rms wave height ratio based on the linear sum of the component waves. Note also that the rms forces used to calculate the force ratios are derived from corresponding Pierson-Moskowitz wave tests (see section 4.2.2).

With snatching absent in the submergence tests the unfiltered versions of the graphs are very close to the filtered ones. These in turn are broadly similar to the filtered versions of the equivalent ratios in the standard test case.

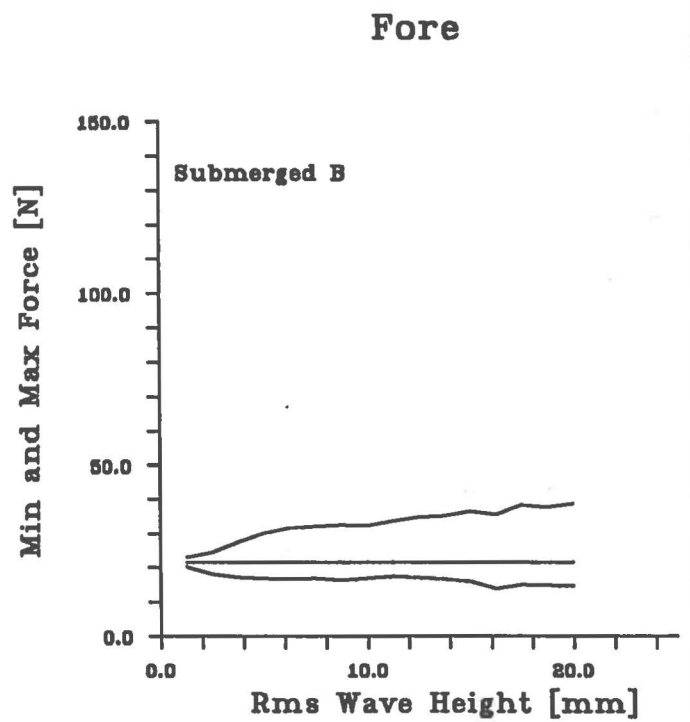
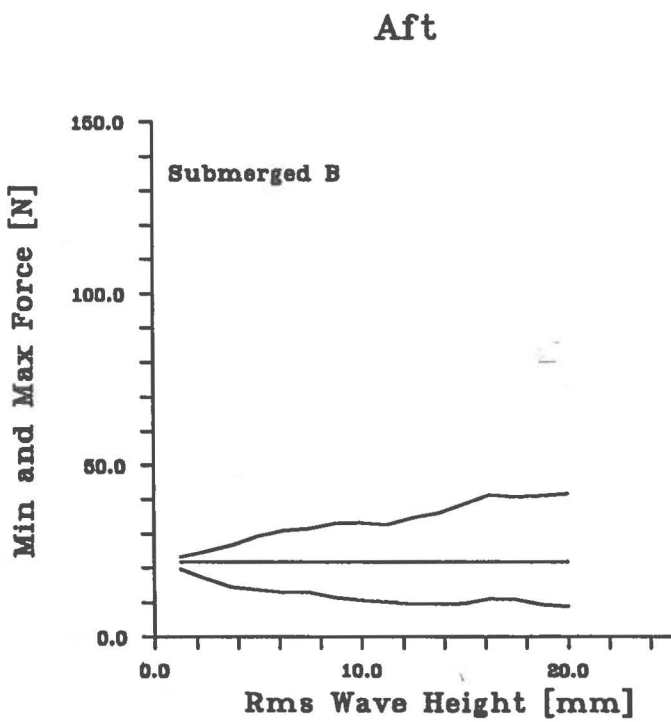
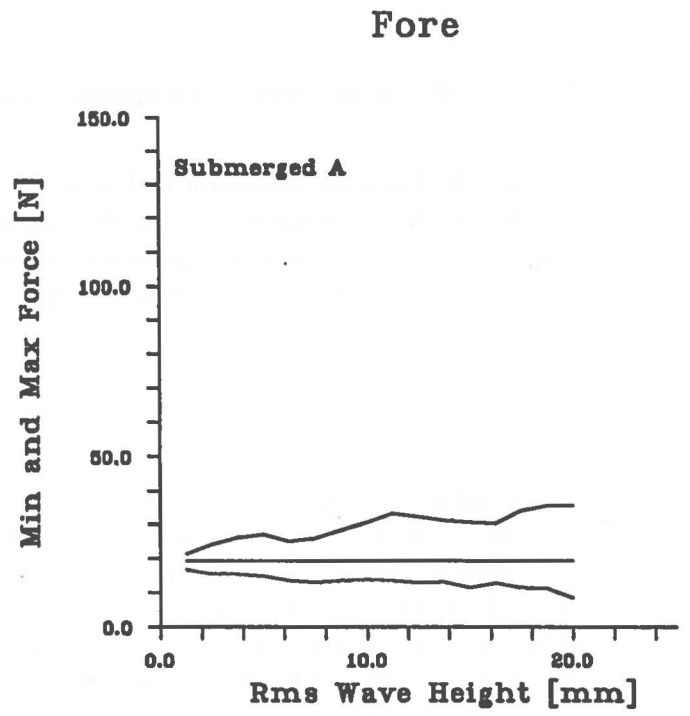
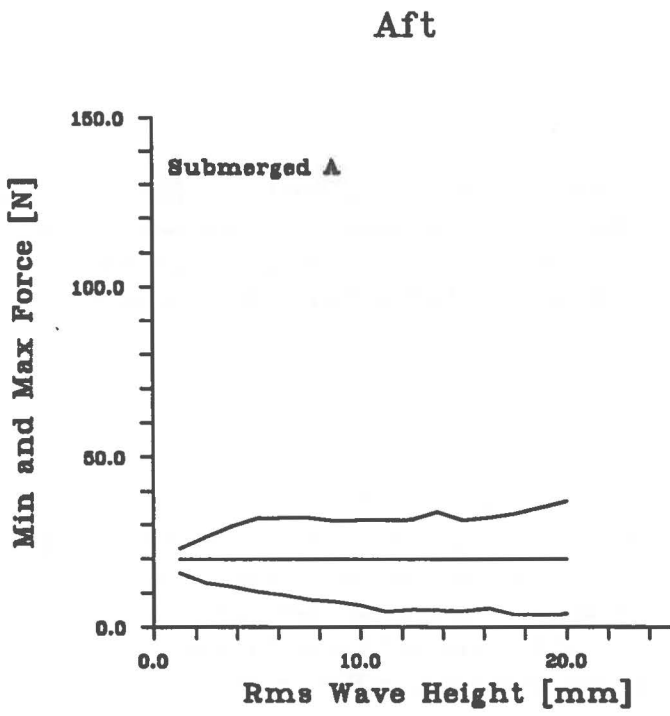


Figure 7.6: Minimum and maximum forces in freak waves varying submergence

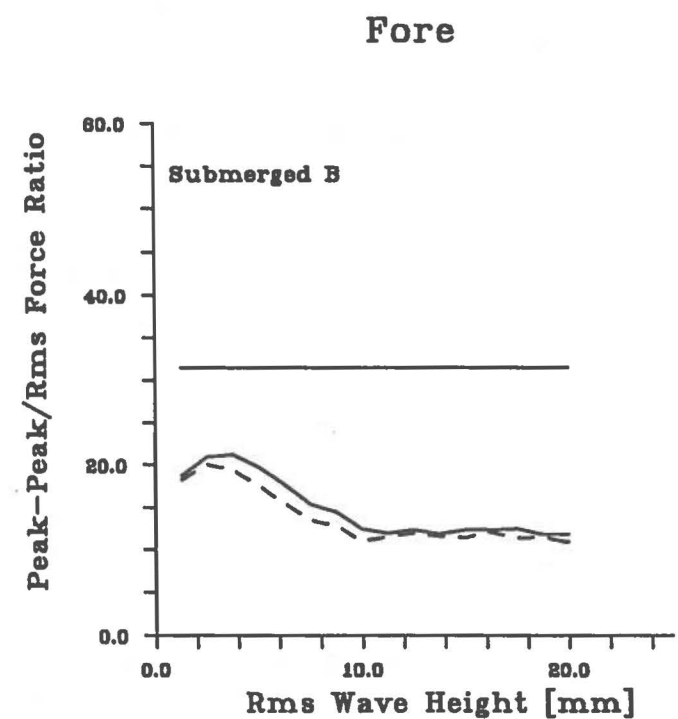
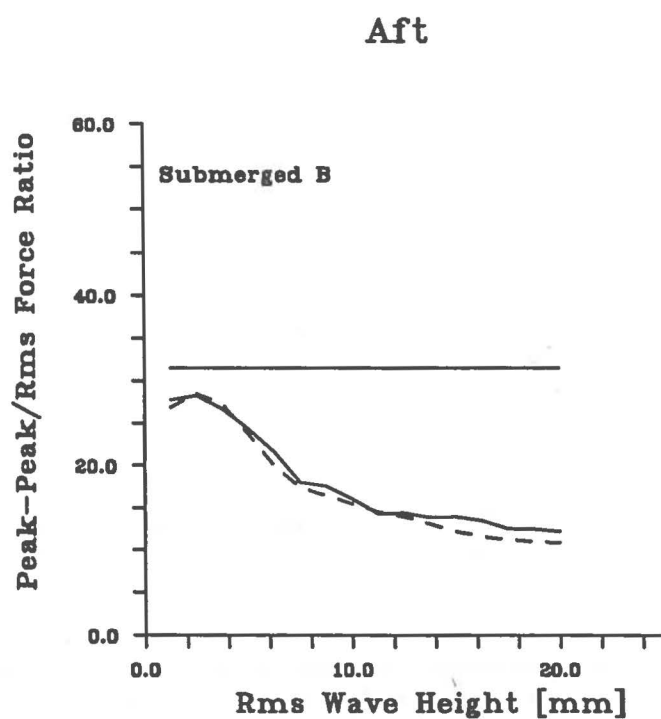
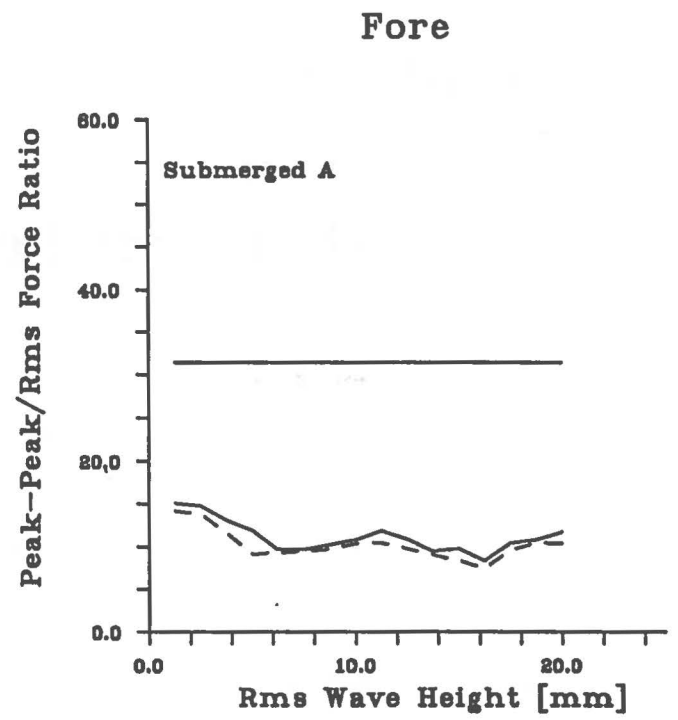
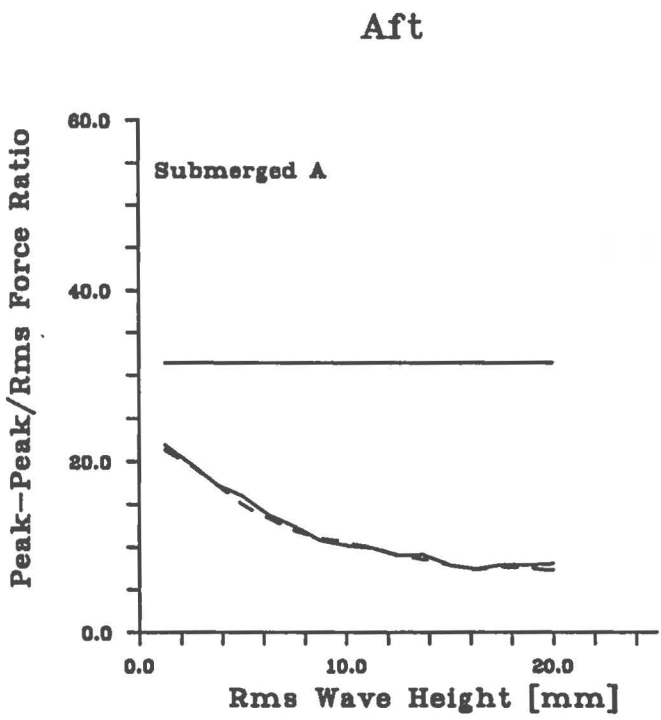


Figure 7.7: Peak-peak/rms force ratios in freak waves varying submergence

Chapter 8

Duck shape variation

The shape of the duck has an effect on the forces on it. Two aspects of shape variation are investigated in this work: corner roundness and width variation.

Rounding the duck corners can reduce the forces on it but without necessarily reducing its efficiency. Rounded corners reduce the losses in the flow of the water on the duck surface and also permit smoother flow around the duck in large waves. Early versions of the duck had very sharp corners but more rounded versions have evolved since. This chapter investigates the effect on the forces with further corner rounding.

The effect of width variation is also investigated in this chapter. So far large wave forces have only been tested in a narrow tank where force is accurately proportional to width. These tests need to be repeated in a wide tank for a range of widths that are likely to be used at full scale. In particular the usefulness of the wave force coefficient needs to be confirmed if it is to be used for solo duck design.

8.1 Effect of shape variation on force records

The most striking thing about the force records is the similarity between them. The records essentially only differ in the magnitude of the forces. The timing of the slack, snatching and oscillation periods are very close.

8.1.1 Fore force records

Figure 8.1 shows a series of force records measured in a freak wave on a duck with various shapes. The top trace is the standard test case. The sequence shows the effect of rounding the corners of the duck and the effect of width variation on the duck.

Apart from the magnitude of the forces the records show a similarity that resembles repeat runs under identical conditions (see figure 4.2). The difference in magnitude is to be expected. There is a small reduction in snatch force as a result of rounding the duck corners and there is a reduction in force on the narrow duck and an increase in force on the wide duck. The largest peak force on the wide duck has been clipped as it has exceeded the measuring range of the load cell.

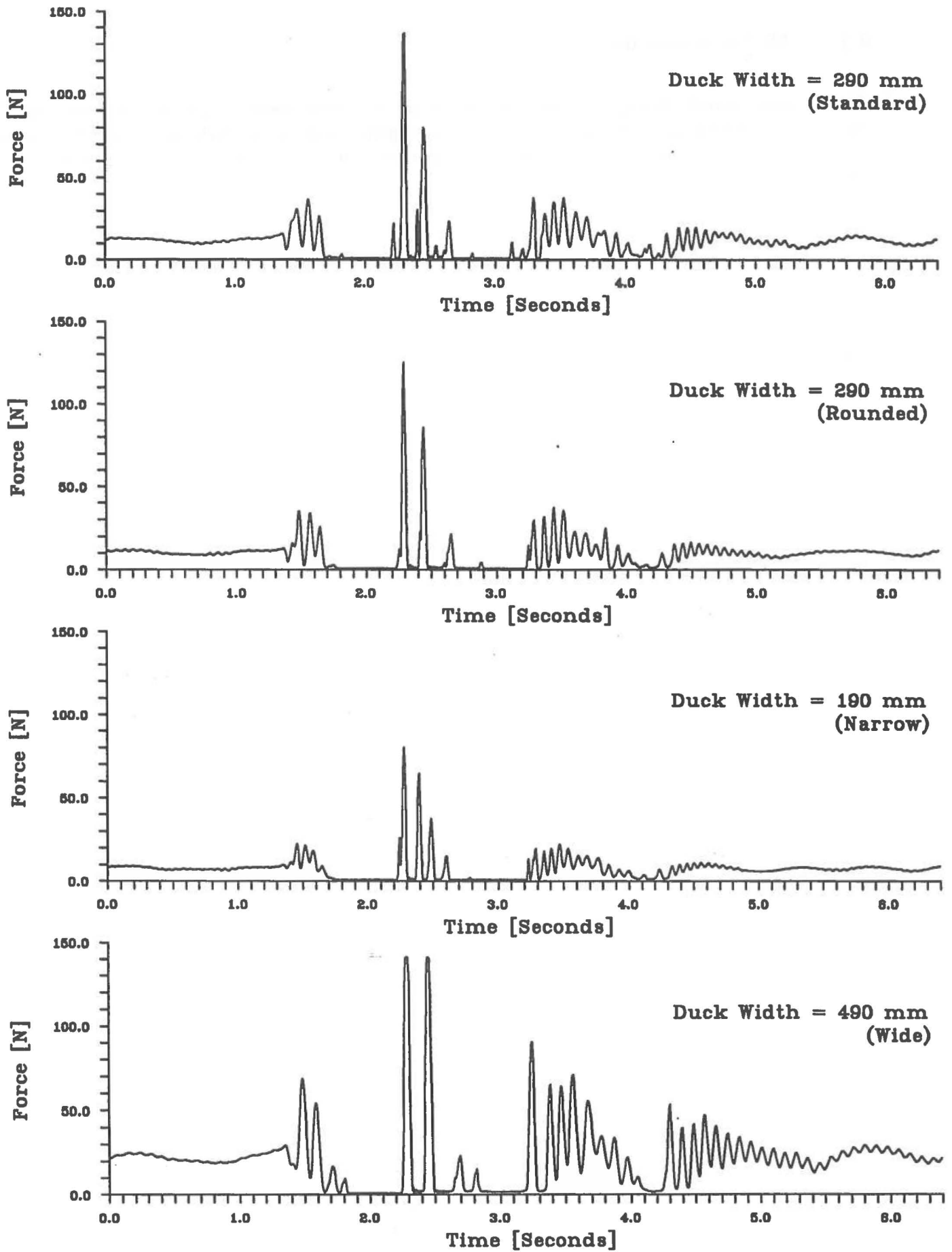


Figure 8.1: Fore force records in a freak wave varying duck shape

8.1.2 Aft force records

The aft force records display a similar pattern to the fore force records. Figure 8.2 shows the aft forces corresponding to the forces in figure 8.1. Here again rounding the duck reduces the force while changing the width also results in a corresponding change in force. The records are otherwise very similar.

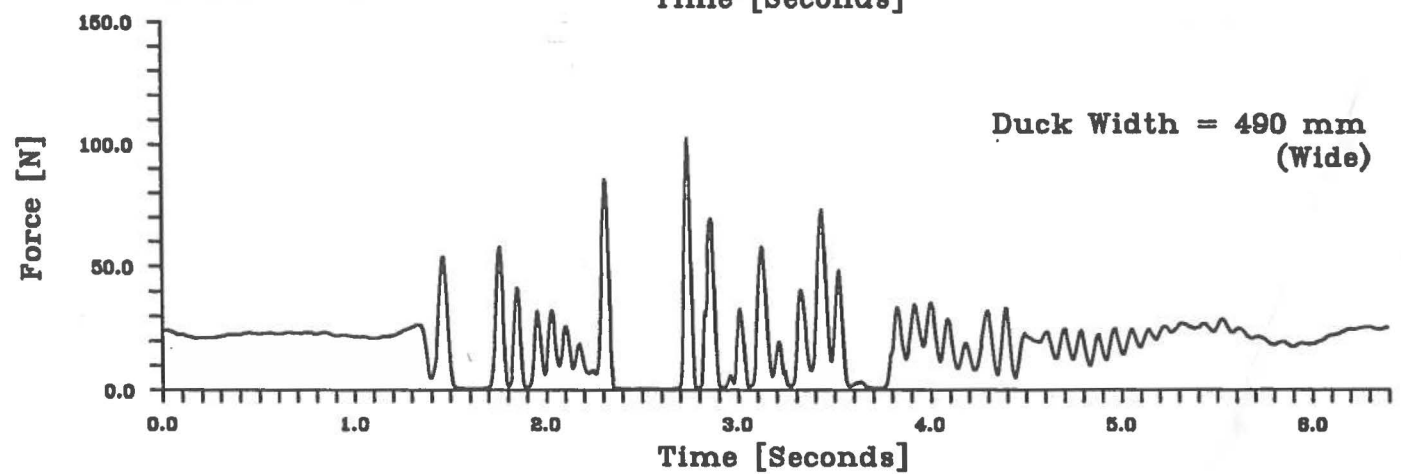
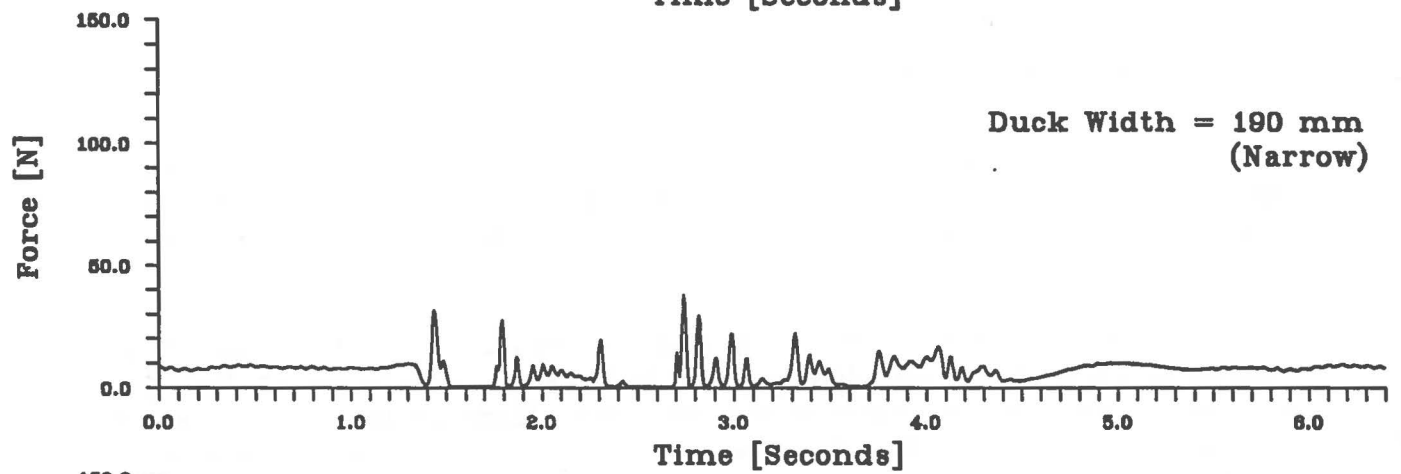
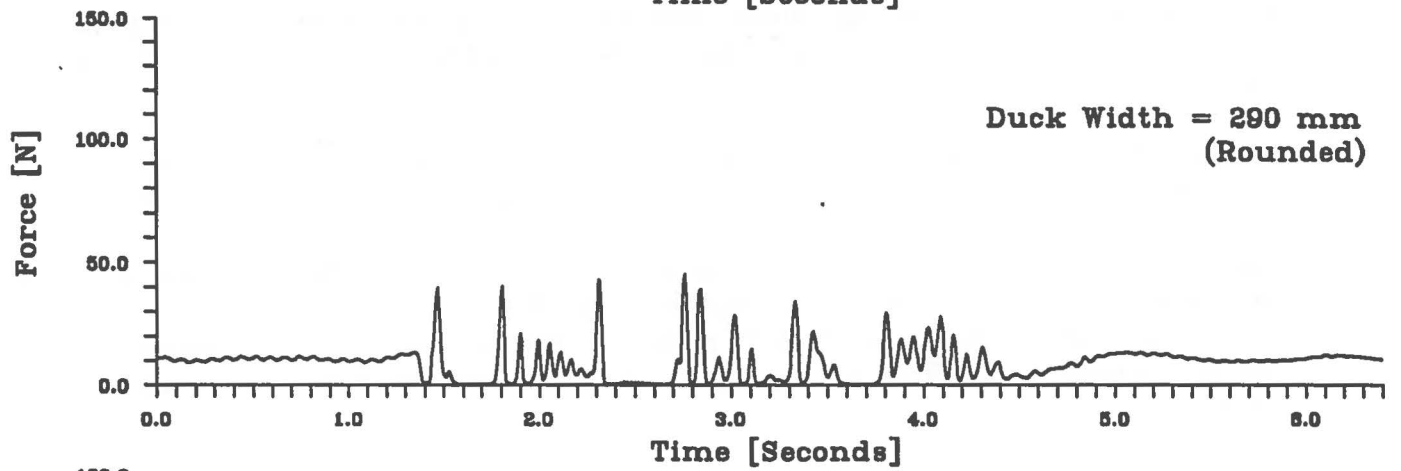
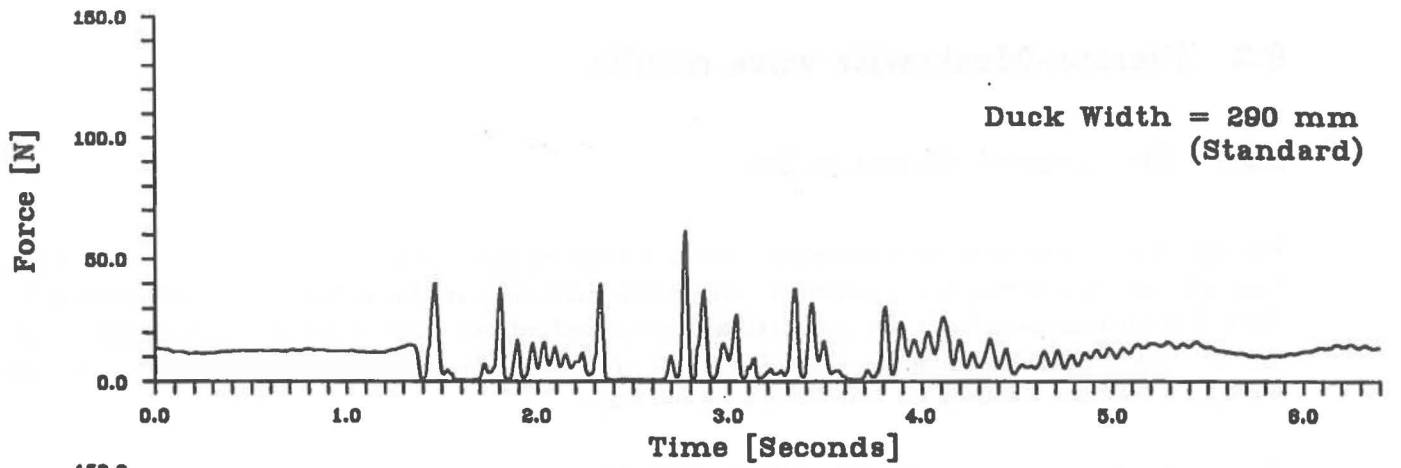


Figure 8.2: Aft force records in a freak wave varying duck shape

8.2 Pierson-Moskowitz wave results

8.2.1 Rms force coefficient ratios

The rms force coefficients are presented here as a ratio to the standard test case (see figure 3.10). Figure 8.3 shows the rms force coefficient ratios. The solid lines are the ratios of the coefficients using the unfiltered records in both the presented and the standard test cases while the dashed lines are the ratios of the coefficients using the filtered versions of the corresponding records. The horizontal solid straight line is also included to mark a one to one ratio.

In all the graphs the unfiltered and filtered versions of ratio are very close. There is a matching contribution to rms force from snatching in each of the presented test cases compared to the standard test case.

Rounding the duck corners has the effect of reducing the rms forces. This is a welcome trend from the point of view of survival although it is not clear what effect this will have on the efficiencies.

Changing duck width does not produce a significant change in force coefficient. There is as much variation within each of the test cases as between them. Note that the definition of force coefficient includes duck width. This is why the force coefficient ratios are presented rather than force ratios. The ratios appear to be sufficiently close to make the force coefficient useful for the range of widths tested.

8.2.2 Peak-peak/rms force ratios

Figure 8.4 shows the peak-peak/rms force ratios. These should be compared with the force ratios in the standard test case (see figure 3.11) and the peak-peak/rms wave height ratios (see figure 2.2). The solid lines are the ratios using the unfiltered force records while the dashed lines are the ratios using the corresponding filtered records.

All the graphs show a similar trend to the standard test case in both the unfiltered and filtered versions. In aft, oscillations are induced from the fore wire and cause the peaks to be larger than the underlying forces while in fore the main deviation is at the higher amplitudes where the snatch peaks become the dominant force. The filtered versions of the ratios are similar in magnitude to ratios in the measured wave heights.

Aft

Fore

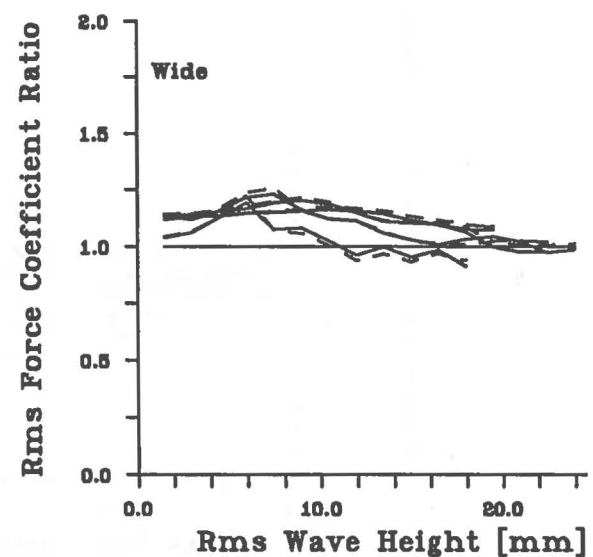
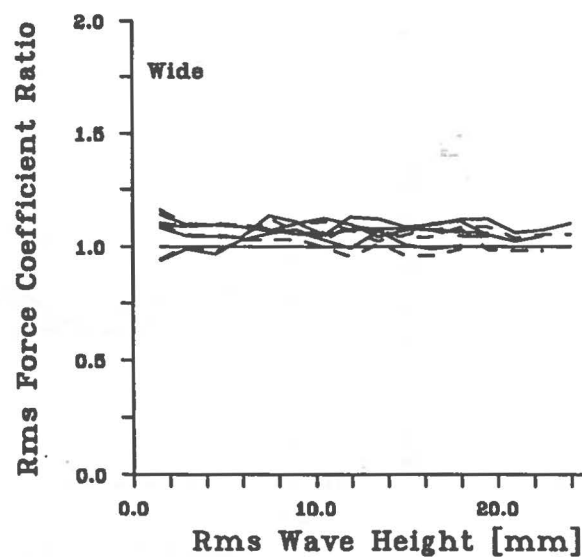
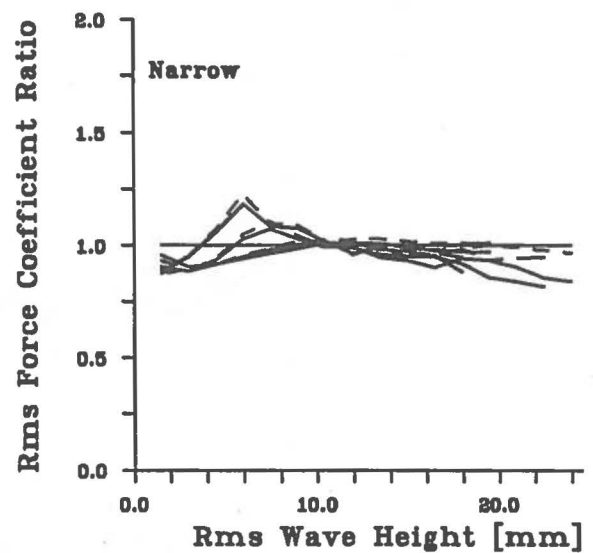
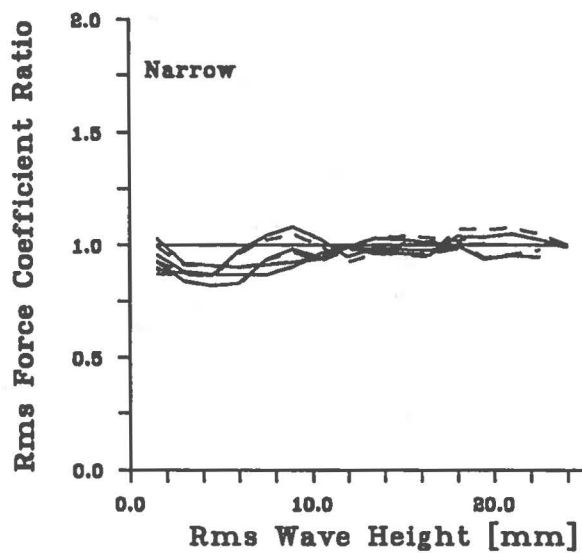
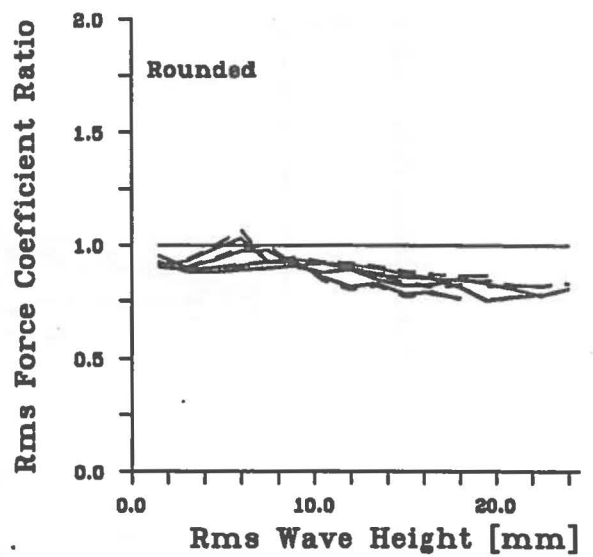
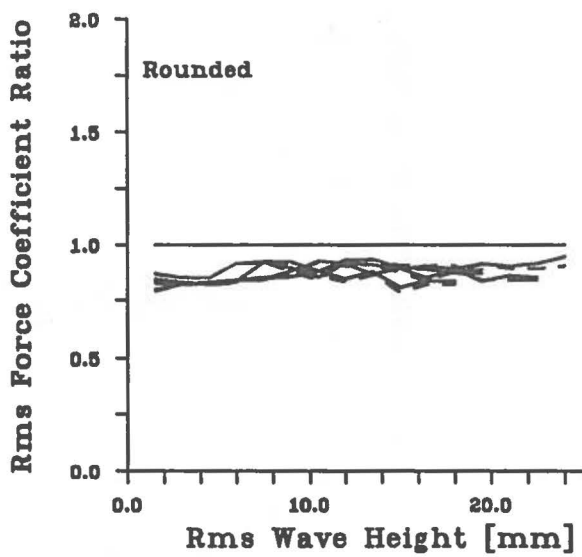


Figure 8.3: Rms force coefficient ratios in Pierson-Moskowitz waves varying duck shape

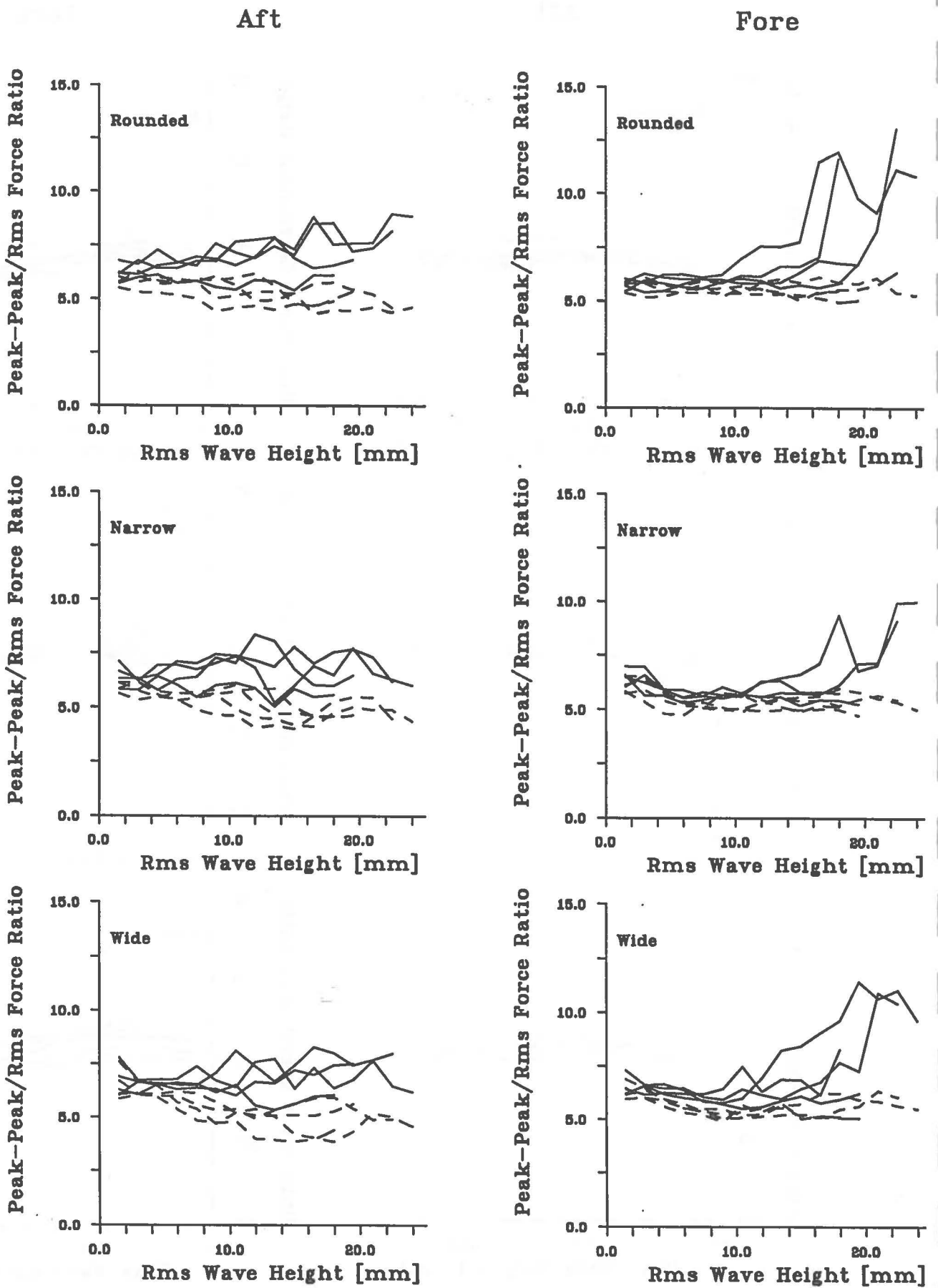


Figure 8.4: Peak-peak/rms force ratios in Pierson-Moskowitz waves varying duck shape

8.3 freak wave results

8.3.1 Peak-peak/rms force ratios

The freak wave peak-peak/rms force ratios are shown in figure 8.5. These should be compared with peak-peak/rms force ratios in the standard test case. The solid lines are the ratios using the unfiltered versions of the force records while the dashed lines are the ratios using the corresponding filtered records. The horizontal solid straight line is included to represent the theoretical peak-peak/rms wave height ratio based on the linear sum of the component waves. Note also that the rms forces used to calculate the force ratios are derived from corresponding Pierson-Moskowitz wave tests (see section 4.2.2).

All the results are similar to the standard test case except for the unfiltered versions of fore force in the narrow and wide ducks. It seems that the standard test case is the worst for snatch force to width ratio.

The two right-most unfiltered fore data points in the wide duck have in fact been clipped and should be a little heigher. The forces have exceeded the measuring range of the load cells (see figure 8.1).

Aft

Fore

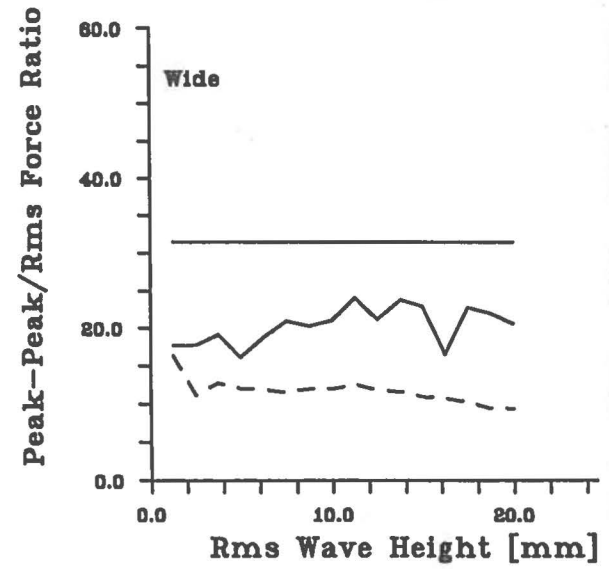
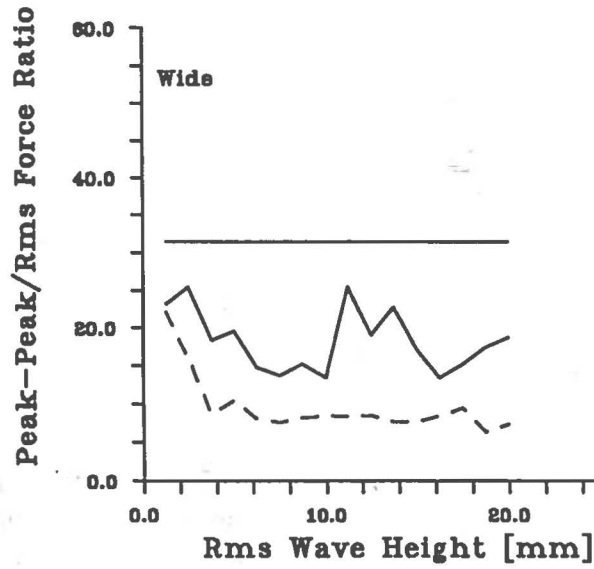
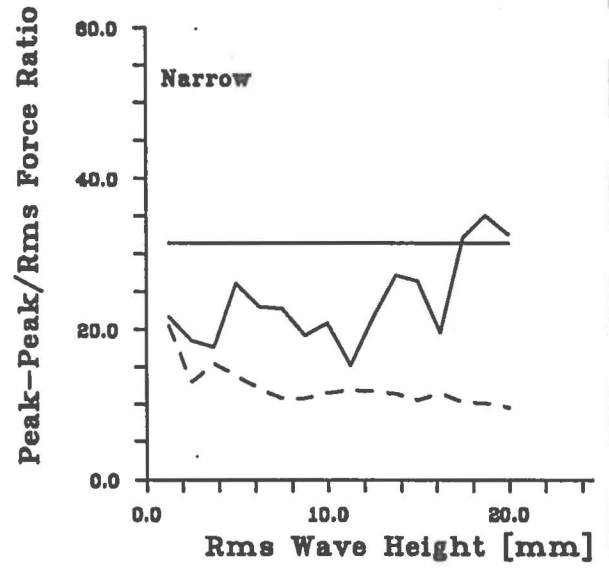
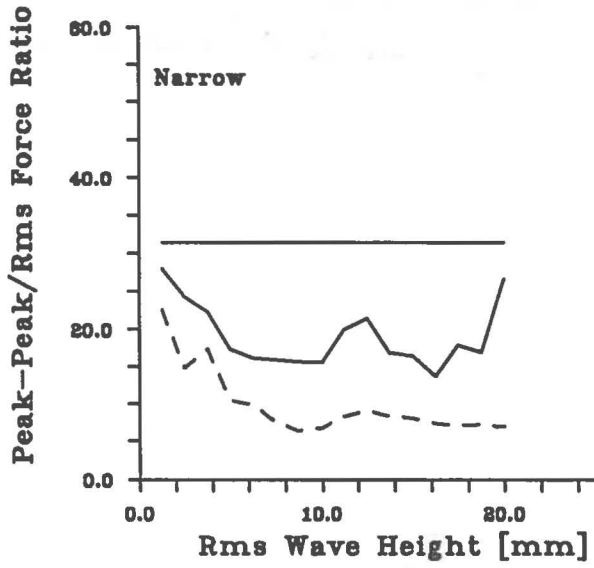
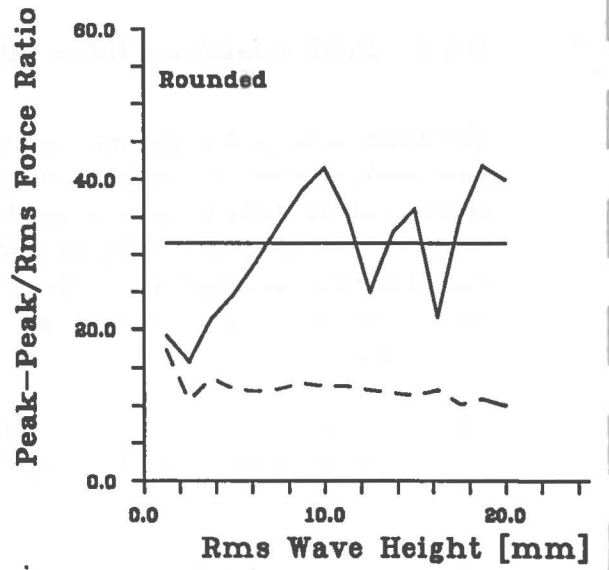
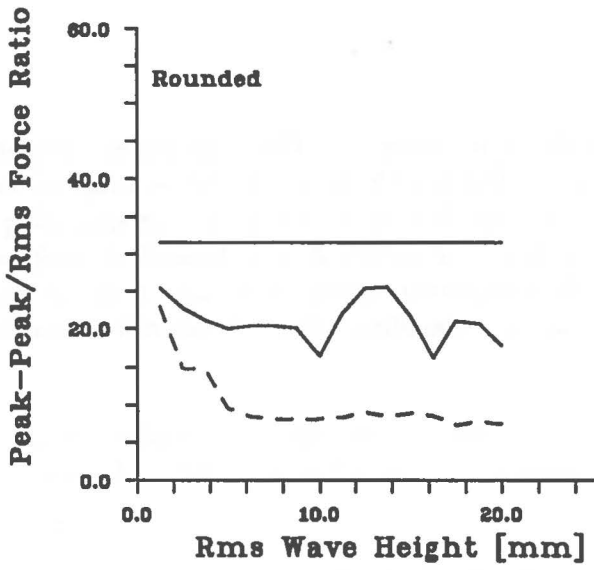


Figure 8.5: Peak-peak/rms force ratios in freak waves varying duck shape

Chapter 9

Further work

The purpose of this work is to test models of the solo duck in representative wave conditions that are likely to occur over the life of a full scale device. The results presented here go a long way both to illustrate the problems that face the designer of tension leg devices and also to providing specific results for use in preliminary designs of the solo duck for the purpose of costing.

The tests do not model any specific design of a solo duck but instead they try to model certain generic setups which form building blocks for engineering solutions. The test results in each of these setups give an idea of the effect of incorporating it into the full scale design. The engineering implementation is unlikely to be identical to any of the model setups but will either be an accurate equivalent of or a close approximation to one or a combination of them.

A continuation of this work would include the following:

- Further test setups are needed to give a designer results for a wider selection of building blocks. These could include:
 - Tests on a duck that is fixed in pitch to investigate the possibility of applying the large force, limited motion approach to the pitch degree of freedom as well. Duck capsize would be avoided.
 - Tests varying the ballast in the duck to investigate the effect of a change in buoyancy and density.
 - Tests incorporating force limiting to investigate the possibility of absorbing the snatch energy with a constant force.
 - Tests with tension legs that are also designed for compression to compare with a snatch avoidance approach.
- A method is needed to generate waves with varying degrees of peak-peak/rms ratios so that tests can be done in conditions that are in between the two extremes of random waves and freak waves.
- The snatch phenomenon is very dependent on the characteristics of the force measuring rig. The present rig was not designed with snatching in mind but has nevertheless proved to be useful. Ideally a new rig should be designed to be as stiff as possible to prevent all sources of resonance and compliance other than those that are being modeled.

Further work could be carried out specifically for the solo duck with a view to designing and costing it or using simpler shapes for the purpose of investigating solutions to the snatch phenomenon in general.

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