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Response of a vessel to waves at zero ship speed: preliminary full scale experiments

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Abstract

The objectives of these experiments were to:

a) Determine the procedure required to obtain synchronised motion and wave time series.
b) Collect sufficient data for valid comparison with empirically and theoretically derived predictions of pitch heave and roll response of the chosen vessel.
c) Identify the effect of the following on vessel response:

- Wave direction (vessel heading)
- Tether height
- Steadying sail
- Flopper stopper

d) Measure the transverse metacentric height of the vessel.
e) Assess the value of calm water roll decay tests for roll motion characterisation.

Two types of experiment were conducted – free roll decay tests and irregular wave tests. An inclining test was also conducted. The vessel used was a 10m sailing yacht. Motions were recorded for the free roll decay tests with and without the mainsail hoisted, in very light winds. The irregular wave tests were conducted again in very light winds with the vessel anchored. Motions were recorded with and without the mainsail hoisted, and with sails down for a range of wave headings. Wave direction was altered by roping the vesssel across the waves. Measurements were also taken for one set of conditions with a flopper-stopper deployed. The waves were measured both by remote, unsynchronised CMST wave recorders and a previously untried wave buoy deployed from the vessel generating data time-synchronised with the motions data.

Analysis of the roll decay tests yielded damping ratios β of 0.079 and 0.025 for mainsail hoisted and mainsail stowed respectively. The roll period of 3.8 sec did not change significantly with the hoisting of the mainsail, and was very similar to the peak roll response frequency in the irregular wave tests. This compared with 3.64 secs predicted by a linear single degree of freedom system model using a roll added inertia coefficient of 0.3

The effect of the flopper-stopper and the mainsail on roll were quite remarkable. The flopper-stopper had no discernible effect on the roll RAO, whereas the ratio of amplitude peaks for mainsail:no mainsail was 2.4 – comparable with the effect seen in the roll decay tests. This was contrary to the effects calculated using a somewhat simplistic drag coefficient model.

The roll RAO did not show any clear change with vessel heading varying from 90 to 150 degrees; this may be to wave directional spreading.

The wave energy during the experiments was very low. Consequently the load on the anchor cable was negligible and the wave buoy comparison with the CMST recorders was insufficiently accurate to provide useful calibration data.

The roll motion time series exhibited a beating characteristic similar to that often observed in swell waves.

The conclusions were as follows:

- The mainsail had a far greater influence on roll damping than the flopper-stopper. This was contrary to expectations from elementary engineering analysis. The source of air damping in particular should be a subject of further study.
- The roll decay tests provided a useful comparative indication of roll response in irregular waves.
- It was not possible to determine the influence of the tether on motions under the benign conditions experienced.
- There is a need to find a better method of estimating wave direction.
- The wave buoy should be calibrated in larger waves.

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1 OBJECTIVES

- Determine the procedure required to obtain synchronised motion and wave time series.
- Collect sufficient data for valid comparison with empirically and theoretically derived predictions of pitch heave and roll response of the chosen vessel.
- Identify the effect of the following on vessel response:
– Wave direction (vessel heading)
– Tether height
– Steadying sail
– Flopper stopper
– Measure the transverse metacentric height of the vessel.
- Assess the value of calm water roll decay tests for roll motion characterisation.

2 METHODOLOGY

2.1 Inclining experiment

The roll motion of a vessel depends on its transverse metacentric height.Whilst this may be estimated from the hull shape and mass distribution estimate, it is usually more accurately determined by an inclining experiment. A known heeling moment is applied to the vessel (calm water, no wind, unrestrained) and the resulting (small) heel angle measured. The freeboard fore and aft is measured in order to determine the vessel displacement from the lines plan. The transverse metacentric height GM_T is then determined from the small angle stability formula

$$heeling`moment = \Delta g GM_T \sin j \qquad (2.1)$$

Where Δ is the mass displacement

j is the measured heel angle

The result then enables the linear roll restoring moment coefficient to be calculated. When combined with the vessel hydrostatics (from Maxsurf software in this instance), the VCG may be found. Provided an accurate record of the vessel condition during inclining is noted, variations in load condition during subsequent experiments can then be accounted for.

2.2 Roll decay test

A heeling moment is applied to the vessel (calm water, no wind, unrestrained) then suddenly released. The resulting roll angles are recorded. Analysis of the time series yields the roll period and damping coefficients which may be compared with theoretical or empirical predictions.

The classic (Froude) roll analysis takes the form

$$\frac{d\varphi}{dn} = k_1\varphi + k_2\varphi^2 \qquad (2.2)$$

Where j is the roll angle amplitude

n= swing no

k1, k2 are damping coefficients

The conventional linear single degree of freedom damping analysis yields a damping ratio β from

$$\ln\frac{j_i}{j_{i+2}} = 2bp \qquad (2.3)$$

Note that the factor 2 is omitted in some texts.

There is a range of other analysis methods all yielding similar information.

The measured roll period may be compared with that from the solution to the 1 dof undamped roll equation

$$w_0 = \sqrt{\frac{gGM_T}{k_{xx}^2(1+s_x)}} \qquad (2.4)$$

Where w_0 is the natural undamped roll frequency

s_x is the roll added inertia coefficient. This is the roll polar mass moment of inertia of the fluid accelerated by the roll motion, expressed as a fraction of the roll polar mass moment of interta of the vessel.

k_{xx} is the roll gyradius, determined from detailed mass distribution estimates

GM_T is the transverse metacentric height

The damped period ω and undamped period are related by

$$w = w_o\sqrt{1-2b^2}$$

The roll period and damping factors may then be compared with equivalent values determined from experiments in waves.

2.3 Response to irregular waves

The Response Amplitude Operator (RAO) for each motion may be obtained by measuring the time series of both the wave elevation and the motion response , converting to amplitude spectral density (by FFT) and dividing the latter by the former. The RAO is usually a function of wave encounter angle and, for nonlinear responses, motion amplitude. If the two time series are synchronised and the wave velocity and geometry known, the data can be used later for comparison with a time domain motion prediction. Motion time series were readily obtainable from the TSS motion sensor. Time series synchronisation was not possible with the CMST recorders in their existing configuration (it would require a redesign of the externally supplied data logger or a full description, calibration and signal conditioning of the pressure sensor output). However, CMST had a long term loan of a wave buoy from Incat Designs Sydney, the output of which could be recorded realtime by the same system as the TSS sensor. This wave buoy had not been dynamically calibrated or used in the field. It was proposed to use the experiment to calibrate the device against a bottom-mounted and surface-suspended CMST recorders. This would provide amplitude calibration but not phase calibration (between wave surface elevation and wave recorder signal).

The source of largest experimental uncertainty was likely to be from variation of wave encounter angle. This presents in two forms. Firstly there will be a variation over the duration of the recording. Visual observation provides an objective tool for rejection of a poor quality data set. Secondly there will be a spread of direction with frequency and within each frequency which is more difficult to estimate visually. Whilst the effect of a known spreading can be calculated from the unidirectional RAOs, the process is not reversible. This is a drawback of all full scale seakeeping experiments.

With the above considerations in mind, the optimum length of a data set is a trade off between statistical accuracy of the spectral processing and the variability of the environmental conditions. Previous experience suggests that 4 data sets each of 5 minutes duration are often a reasonable compromise.

3 EQUIPMENT

3.1 Vessel

The vessel of opportunity used was a Van de Stadt 34 design *Panache II*. The lines plan was input to Maxsurf (for hydrostatics) and Seakeeper (for pitch and heave predictions). Principle characteristics are shown in Table 11-1

The yacht was a typical 1980s cruiser-racer, subsequently converted for cruising. It had a lead fin keel and a spade rudder, with ¾ rig . The mainsail used in these experiments was a short luffed, short battened cruising main of dimensions shown in Table 11-2

The vessel was equipped with a flopper-stopper (paravane). This consisted of a board 0.72m by 0.47m centrally hinged with a 4kg weight attached. It hinged closed on a downward motion, providing minimal drag. It opened flat in upward motion to generate motion-resisting drag. The use of such devices is considered by many sailors to be a cheap and efficient means of reducing roll motion when the vessel is stationary. The device used was much larger than paravanes used by fishing vessels ((Helmore 2000), which rely largely on generating lift whilst the vessel is under way.

3.2 Waves

The Incat wave buoy comprised a linear accelerometer mounted vertically in a spherical buoy. The buoy had a 7Kg mass attached 1.5m below its waterline to minimise any tendency to deviate from upright. It was powered by an internal alkaline battery through a regulator built by CMST. Prior to these experiments it had not been compared with other wave measuring devices. The Incat wave buoy was intended for deployment from the vessel, on approximately 15m cable.

The CMST wave recorders are portable pressure sensors attached to data loggers. They are pre-programmed and downloaded from a PC via the serial port. The recorders can be deployed either on the seabed, or surface-suspended from a float. They are stand-alone, with no method of accurate synchronisation.

They are usually set at 2Hz sample rate and in this mode can record approximately 9 hours of data.

3.3 Wind

The CMST hand held cumulative reading anemometer was used to record windspeeds at regular intervals at a known height above sea level.Wind direction was measured using a hand bearing compass and masthead wind indicator.

3.4 Current

Ocean currents were negligible at the chosen sites.

3.5 Tether

The CMST Yakoma load cell was used to measure anchor tether load. It had a range 200-5000N and was attached to the anchor snubber. Tether vertical and horizontal angles were estimated visually in this instance.

3.6 Motions

The TSS sensor was used to measure pitch, heave and roll. It was also used to measure static heel angle during the inclining experiment. It was set at 8sec (short) bandwidth in order to minimise the effects of lateral accelerations. A full description is provided in (TSS-Ltd. 1992)

3.7 Vessel orientation

Ship's compass and a hand bearing compass were used to measure wind and wave encounter angles.

3.8 Data acquisition and conditioning

All signals acquired on board were analogue DC. The Daqbook system was used, with low pass 3^{rd} order Butterworth filters set at 20 Hz. The signals were all acquired at 100Hz sample rate; details are shown in Table 11-3.

3.9 Power supplies and grounds

The ship supply at 12V DC was used to power the laptop PC, load cell and Daqbook. The ship's 140W 240V inverter was used to power the data acquisition rack. Two dedicated 12V wet cell batteries were connected in series to provide 24V power to the TSS motion sensor.

All negatives of signals were connected to the same common ground as supply at the rack. The 12V power supplies were connected to ship ground through the negative wire, as per usual ship supply practice. The TSS ground (separate from the supply negative) was connected to the ship negative rail via a cabin light fitting. The 240V inverter connected the negative, 240V neutral, 240V ground and case together. The supply and signal grounds were connected at the rack.

4 PROCEDURE

The data acquisition system was first set up in the laboratory and a series of runs taken to check for noise and channel cross-talk. The equipment was then installed on the vessel in its berth and further noise checks taken. The trials data were collected on two separate days at different locations, in order to comply with time and weather constraints.

4.1 Inclining experiment

On 28 June 2000 the vessel was moored from the bow to the FSC works jetty in very light winds and no waves. The vessel inclining condition is shown in *Table 11-4*. 30 second data sets were taken when there were no waves evident or other vessels moving nearby. A heeling moment was applied by hanging a 25 litre water container (filled with sea water) from the spinnaker pole set transversely from first the port then the starboard side. Zero datum runs were recorded with the pole rigged and the water bottle floating in the water attached by a rope tackle. On recovering the water container at the end of the experiment a small air gap was evident which was probably present throughout the measurement period. The container was weighed before and after the experiment using bathroom scales, revealing a 2% reduction in weight. The crew and dinghy were on board during the inclining experiment. Windspeed was 2.6m/s measured at 3m above sea level over a 30 second period midway through the experiment. The vessel heading was 040°, in line with the wind. Wave measurements were not taken , as visual inspection revealed height of the order 5mm, less than the resolution of the available instruments.

Freeboards were then measured by the crew in the dinghy, using a metal tape sighted for vertical alignment. The datum was the extension of the deck and hull surfaces; the deck edge had a small radius, approximately 5mm.

4.2 Roll decay tests

The vessel was moored from the bow to the FSC works jetty in very light winds and no waves. A noise check was conducted. Roll was initiated by the crew moving across the boat in phase with the natural roll period. The crew then remained stationary whilst the 30 second data acquisition period ensued. Three runs were conducted, then the mainsail hoisted and sheeted on the centreline and a further 4 runs conducted (Table 11-1). The crew and dinghy were on board during these tests. Windspeed was 1.8m/s measured at 3m above sea level over two 30 second periods near the start and end of the experiments. The vessel heading was 050°, in line with the wind. It was originally intended to deploy wave buoys so as to measure the vessel-generated wave field, but visual inspection revealed height of the order 5mm, less than the resolution of the available instruments.

4.3 Response to irregular waves

4.3.1 16 June 2000, Longreach Bay

The first set of trials was conducted at Longreach Bay, Rottnest Island in conditions of light winds and low seas. The CMST recorders were programmed prior to departure. A pair of CMST wave recorders were deployed outside the reef as part of a separate project, then the vessel was anchored in 2.7m water depth at position S 31° 59.396' E 115° 31.805'. A CMST recorder was deployed on the sea bed in fixed mode from a line at the bow, then the other instruments were deployed. A second CMST wave recorder was attached directly below the wave buoy but it did not work. The wave buoy was deployed from the stern, approximately downwind. A series of runs were recorded (see*Table 11-11*) in accordance with the methodology described in 2.3 with the exception that the anchor tether angle was not measured.

The vessel heading was altered by roping across to a mooring buoy located approximately 50m on the port beam. The rope was taken to a cockpit winch via a fairlead on the transom centreline. The load on the rope was negligible (estimated at less than 10Kg).

Video and still photos were taken. After the final run the wave recorders were recovered and the vessel returned to harbour. A further noise check was taken the following day at the berth.

4.3.2 28 June 2000, South Beach

The second set of trials was conducted off South Beach, Fremantle in very light winds and very low seas. The vessel was anchored midway along the dog beach in 3.5m water at approximately S32°04.4' E115°45.0'. Three CMST wave recorders were programmed, a pair was deployed in fixed mode on the sea bed from a line at the bow, the other was attached directly beneath the wave buoy, which was deployed from the starboard (downwind) side. A series of runs was recorded (see *Table 11-12*) in accordance with the methodology described in 2.3 with the exception that the anchor tether angle was not measured.

The vessel heading was altered by deploying a stern anchor perpendicular to the dominant wave direction. Unfortunately this only permitted a small change in vessel heading; it should have been deployed into the waves. The rope was taken to a cockpit winch via a fairlead on the transom centreline.

Whilst the vessel was anchored bow and stern, two runs (31 and 32) were conducted with the mainsail hoisted and sheeted home in line with the wind. This was less than satisfactory, since both a positive and negative wind inflow angle caused a turning moment into the waves (i.e. anticlockwise). With the sail backed (negative inflow angle), the yaw stability was negative The mainsail was lowered after run 32.

A flopper-stopper (paravane) was deployed for runs 35 to 38. It was deployed from the spinnaker pole3.8m off centreline to port, submerged approximately 1m.

Still photos were taken from a point approximately 5m up the mast between runs 28 and 29, to aid estimation of wave direction.

After the final run the wave recorders were recovered and the vessel returned to harbour.

5 RESULTS

5.1 Inclining experiment

The mean inclined angle was 1.01° with a standard deviation of 0.12°. Full details are shown in Table 11-6. The transverse metacentric height in the measured condition was 1.07m. A typical time series (seconds) is show in *Figure 10-1*.

5.2 Roll decay tests

Each run was smoothed using a weighting 5-point moving average, then mean-subtracted. Gross maxima and minima were identified by searching through a decimated version of the data, to avoid spurious local maxima and minima. The 60 second data sets were truncated at 33 seconds in order to eliminate inaccuracies due to low amplitude measurements and low frequency drift (see0 , *Figure 10-5* &*Figure 10-6*). The resulting curves of declining angles *Figure 10-4* were not smoothed, in order to avoid imposing a presumed model on the data. These curves were then processed to yield roll decrement curves (Froude analysis) *Figure 10-5* & *Figure 10-6*and β damping ratios *Figure 10-7*. The roll decrement coefficients and β values are shown in table *Table 11-8* & *Table 11-9*.

5.3 Wave data

On both trials days there was a dominant swell peak and a very small wind wave peak. The wave height on 28 June was close to the minimum at which meaningful results could be expected. For the frequency range 0 – 0.5Hz, the uncorrected significant wave height was 0.2m on 28 June (South Beach) and 0.44m on 16 June (Longreach), as measured by the CMST recorders.

Both the wave buoy and the CMST recorder data sets were processed by the Welch method using a Hanning window on 512 data point segments with 50% overlap where there were sufficient data points in the sample.

High and low frequency cutoffs for the CMST recorders were determined by comparing the spectra from the seabed and floating recorders. It was evident from this process that the floating sensor was too shallow to identify the swell and the seabed sensors too deep to identify the wind waves. A combined spectrum was obtained by using the fixed sensor for frequencies below 0.25Hz and the floating sensor for higher frequencies The wave buoy acceleration spectra were converted to amplitude spectra in the frequency domain , and then to wave slope spectra using the full intermediate depth Airy wave number. The water depth used in the CMST recorder processing was corrected for changes due to tide using *Table 11-13*.

The CMST recorder and wave buoy amplitude spectra were compared as shown in *Figure 10-8* & *Figure 10-9*. Synchronisation was determined from logged deployment times, accurate to approximately 2 minutes. It is evident from this diagram that there was insufficient wave energy to provide for an accurate calibration of the wave buoy, but the spectra were consistent within the limits of experimental error. Therefore the wave buoy spectra were used to obtain RAOs, as they were time-synchronised with the response measurements.

5.4 Motion response in irregular waves

A typical (uncalibrated) motion time series is shown in *Figure 10-10*

The motion and anchor load time series were processed by the Welch method using a Hanning window on 512 data point segments with 50% overlap where there were sufficient data points in the sample. This was the same procedure as used for the wave buoy; all 5 channels were processed simultaneously in the same Matlab program. Sample spectra are shown in *Figure 10-11* & *Figure 10-13*.

Response Amplitude Operators were obtained by dividing the response spectral ordinate by the wave buoy spectral ordinate (amplitude for heave, slope for roll and pitch). The only spatial and temporal uncertainties between the motion responses and the wave field measurements were due to the location of the wave buoy approximately 10m from the vessel. Where more than one run was taken for a particular condition, the RAOs for each run were processed individually then the average taken for all those runs. Note that the RAOs did not approach unity as the frequency tends to zero. This was because the wave buoy overestimated the low frequency spectral ordinates, since any noise in the signal was divided by the fourth power of radial frequency (a very small number at swell frequencies) when converting the acceleration spectral density to amplitude spectral density. This resulted in an underestimated RAO at these low frequencies.

6 ERRORS

6.1 Inclining experiment

The inclining mass was weighed on scales calibrated to +-0.5%. However, the mass was 1.8% less at the end of the experiment. This was due to slight leakage of water from the lid. It was considered likely that most of this occurred when the container was first deployed, so the lesser figure was used in the calculations.

The length of the moment arm was measured to within 0.3% and set horizontally and transversely to within 1°.

The heel angle measurements contained roll oscillations, typically of 0.1° amplitude and 4 second period. This was probably due to waves or wind gusts. The accuracy of the results could be improved slightly FFTing each data set, applying a low pass filter then inverse FFTing the data.

Freeboard measurement errors were estimated at +-0.35%, due mainly to extrapolating the hull-deck datum at the deck radius. This error corresponded to a mass displacement error of 60Kg, as determined from the vessel hydrostatics. The hydrostatics were calculated using a Maxsurf hull representation which was accurate to within approximately 1.5% for displacement (i.e. 75Kg).

6.2 Roll decay tests

The main source of error was the erratic return to datum of the motion sensor reading as the oscillations died out. There appeared to be a low frequency drift induced by the roll motion, starting up as the roll died out e.g. *Figure 10-3* .Consequently, the data sets were truncated at 50%, 33% and 20% to investigate the effect of this drift *Figure 10-5* & *Figure 10-6*. Whilst truncating reduced the influence of the drift, it also decreased the number of data points (from typically 31 swings for 100% to 6 swings at 20%). Irrespective of the level of truncation, the variations in the Froude analysis – often well over 100% - were too large for the results to be of much value. These variations could be considerably reduced by curve-fitting the curve of declining angles, but the requirement to choose a particular model was effectively forcing the data to match theory rather than testing the theory.

The damping ratio β analysis fared rather better, varying with truncation by 28%. The variation between runs was typically 30%.

6.3 Response in irregular waves

A major source of error was in the wave amplitude estimation, comprising two significant components. Firstly, the wave amplitudes were very small, particularly on 28 June, making background noise and instrument response characteristics important. Signal to noise ratio was typically 2% in the acceleration time series, which amplified in the amplitude time series to 5% at 0.1Hz and 20% at 0.05Hz. This resulted in a masking of the swell wave spectrum components.

The second wave error component was in calibration. The wave buoy used had not been compared with other devices except in this experiment. However, since the same instrument was used to process all the vessel response data, comparisons between data sets within these experiments did not suffer significantly from this calibration uncertainty.

Wave direction estimates were also subject to error. Whilst the measurement accuracy of direction was within +-5°, the value recorded was the mean for the perceived dominant frequency. The directional spread of that dominant frequency was not measured, nor were the directions of the subsidiary frequencies.

Measurement errors in the motions were at least one order of magnitude less than the wave errors described above.

The relative errors in the load cell readings were large, owing to the low magnitude of the loads.

7 DISCUSSION

7.1 Inclining experiment

The result was in line with expectations for the style of yacht used, viz a vertical centre of gravity approximately 0.1m above the waterline. The inclining experiment was sufficiently accurate for this preliminary investigation. Accuracy could be improved by using a greater mass and addressing the low frequency drift of the motion sensor.

7.2 Roll decay tests

It was very clear whilst conducting the roll decay tests that the mainsail had a large impact on roll damping. This was born out in the numerical results. The Froude analysis was insufficiently consistent to be of much use. There was an indicative trend for the quadratic damping coefficient k2 to increase when the mainsail was hoisted, with no trend evident in the linear k1 values. k2 is generally considered to represent the wavemaking component of hydrodynamic damping; the very low values for the base condition agreed with the observed lack of roll-generated waves.

The damping ratio β was a more consistent measure. This was somewhat surprising, given the low likelihood of damping being linear with respect to roll amplitude. The damping ratio with the mainsail hoisted was over 3 times greater than for the base condition. This was a similar effect to that found in the irregular wave tests (see 7.3.4). The β value of 0.025 was comparible with values for other vessels at zero speed e.g. 0.036 and 0.031 for a 23m and 36m trawler respectively. (Goudey and Venugopal 1989). *Figure 10-7* shows the variation of β with roll amplitude.

The roll period did not change significantly with the hoisting of the mainsail, and was very similar to the peak roll response frequency in the irregular wave tests.

The accuracy of the roll decay tests might be improved by addressing the low frequency drift in the motion sensor or possibly by analysing the data in the frequency domain.

7.3 Irregular wave tests

For the 16 June tests, the vessel response was large enough to generate motion representative of a slightly uncomfortable anchorage. Using the US Navy discomfort indices outlined in (Martin 1994), the conditions would have rated, on a scale 0->3, at 1 ("increased effort and fatigue"). The 28 June tests, on the other hand, would have rated <1 ("negligible").

7.3.1 Wave amplitude

The measured wave amplitudes may not be accurate, as they were too low to provide a good calibration for the previously untried wave buoy.

7.3.2 Wave direction

As expected, the most difficult parameter to measure and to control was vessel heading relative to wave direction. The measured direction was the most visually dominant one, which tended to be the swell. On occasions it was quite clear that shorter wavelengths held a dominant direction of up to 45 degrees different from that measured. However, the motion response results did not demonstrate a strong dependence on measured wave direction. This observation is discussed further under section 7.3.3

7.3.3 Roll response

The roll RAOs (*Figure 10-14*, *Figure 10-15* & *Figure 10-16*) show a well-defined peak at approximately 0.25 Hz under all test conditions. This corresponded with the natural roll period measured in the roll decay tests. There was no distinguishable trend of roll RAO peak amplitude with wave heading. Model tests in regular 2-dimensional waves e.g. (Schmitke 1978), (Lloyd 1989), (Lloyd and Crossland 1990), show a slight decrease in roll response from 90 deg to 150 deg heading, though results vary considerably with ship type. For measurements in short-crested seas, wave spreading will reduce the magnitude of any such variation. The results were not sufficiently clear to determine whether there was any nonlinear effect with respect to motion amplitude.

The time series (*Figure 10-10*) exhibited a beating characteristic that was also observed by the crew during the tests. It was due to the narrow band nature of the roll response. This was checked by creating a simulated roll motion time series from a white noise signal filtered with the roll RAO. The results showed much the same beating characteristics as the time series recorded in the experiments. The effect of the flopper-stopper and the mainsail were quite remarkable. The flopper-stopper had no discernible effect on the roll RAO, whereas the ratio of amplitude peaks for mainsail:no mainsail was 2.4 – comparable with the effect seen in the roll decay tests. This was the inverse of the effect shown by caclulation of the damping moment using a somewhat simplistic drag coefficient model. Assuming the damping force is a function of drag coefficient, that the drag coefficient for both the sail and the flopper stopper were the same as for a flat plate, and that the fluid velocity is averaged to its value at the geometric centroid, then the flopper-stopper should generate a damping moment of 4.8KNm per degree and the mainsail 1.9KNm per degree. This takes account of the flopper stopper working at 50% efficiency due to it hinging on the downswing. Clearly, the damping effect was not simply flat plate drag. Further, the consistency of the natural roll period implies there was no significant difference in added inertia between devices. The damping does not appear to be an edge effect because the mainsail had a lower edge/area ratio (1.1) than the flopper-stopper (7.3). Both sail and flopper-stopper operate at similar Reynolds number, typically 0.6×10^5. The lack of damping from the flopper-stopper was contrary to the findings of others for trawler paravanes e.g. (Goudey and Venugopal 1989).

7.3.4 Heave and pitch response

Figure 10-13 and their associated RAOs did not show any unexpected features.

7.3.5 Anchor load

The load on the anchor was negligible for most runs, with the anchor cable hanging near-vertical. The peak frequencies in the spectrum correspond with the heave and pitch peak frequencies, suggesting that the load changed as a consequence of the vertical motion at the bow. The mean load was close to the threshold of minimum response for the load cell. Whilst the experiments therefore did not shed light on the influence of tether load on motion response, they did demonstrate that uncomfortable motion can be experienced without any significant tether load.

A two-plane potentiometer based system may have to be built for subsequent experiments, should larger tether loads be found to have a significant influence on motions.

8 CONCLUSIONS AND RECOMMENDATIONS

1. The mainsail had a far greater influence on roll damping than the flopper-stopper. This was contrary to expectations from elementary engineering analysis. The source of air damping in particular should be a subject of further study.
2. The roll decay tests provided a useful comparative indication of roll response in irregular waves.
3. It was not possible to determine the influence of the tether on motions under the benign conditions experienced.
4. There is a need to find a better method of estimating wave direction.
5. The wave buoy should be calibrated in larger waves.

9 REFERENCES

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10 DIAGRAMS

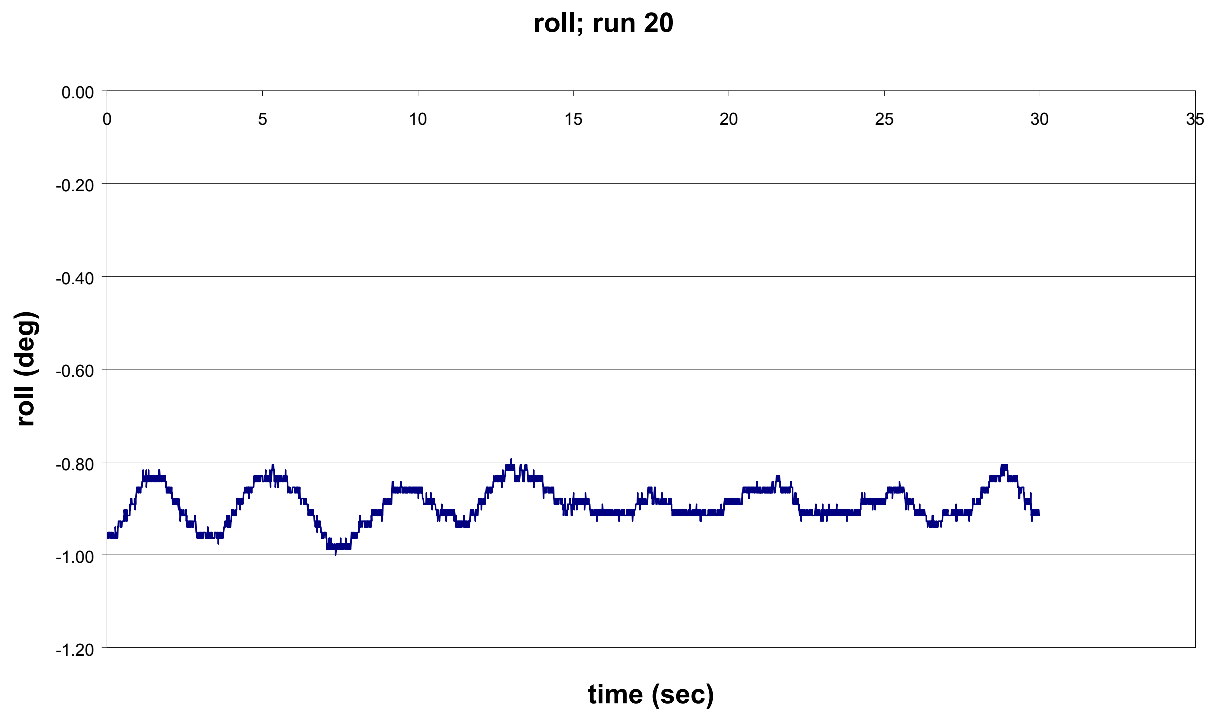

Figure 10-1. inclining expt heel angle: run 20

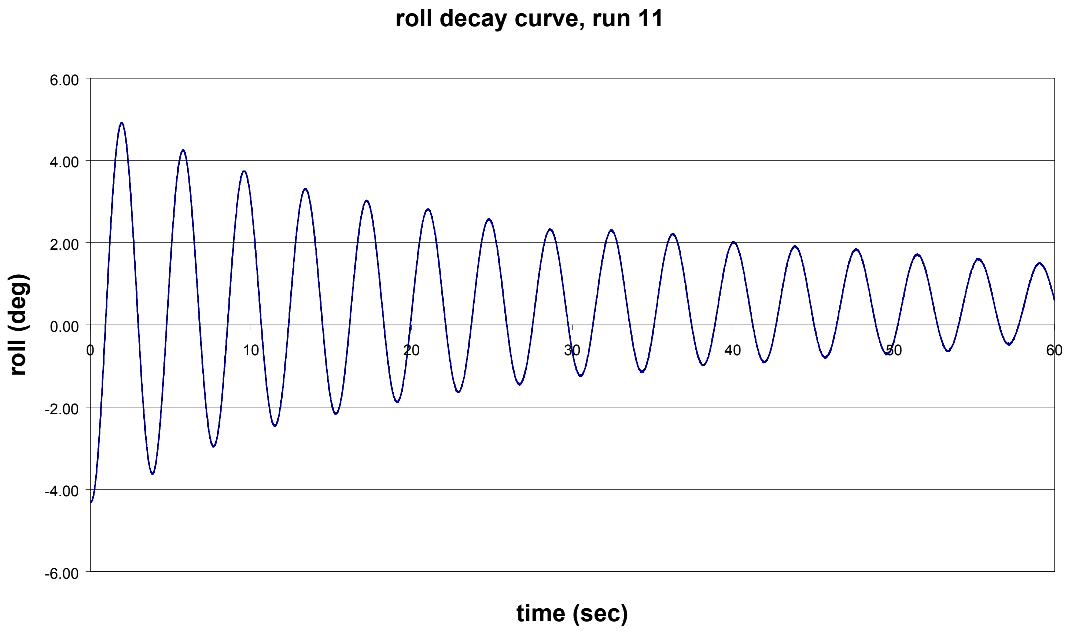

Figure 10-2. typical roll decay curve – no mainsail

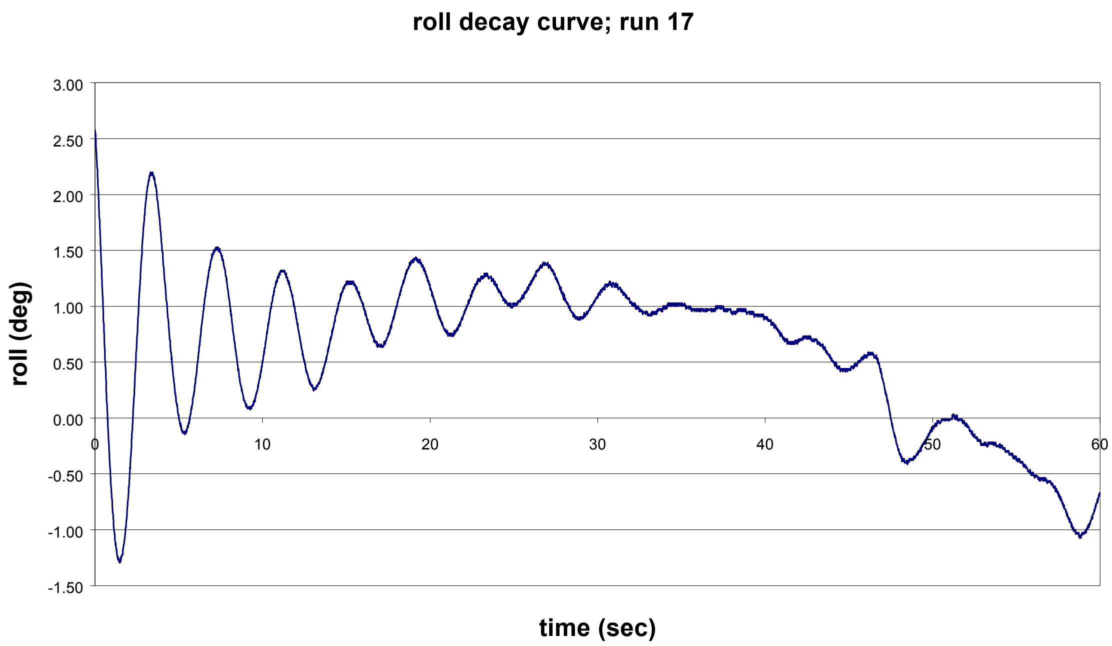

Figure 10-3. roll decay curve - mainsail up

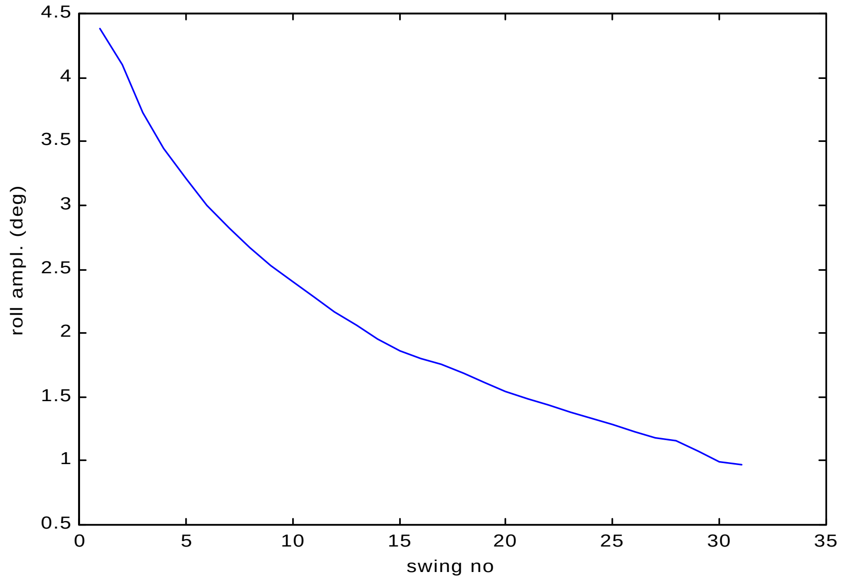

Figure 10-4. typical curve of declining angles: run 11 60 seconds

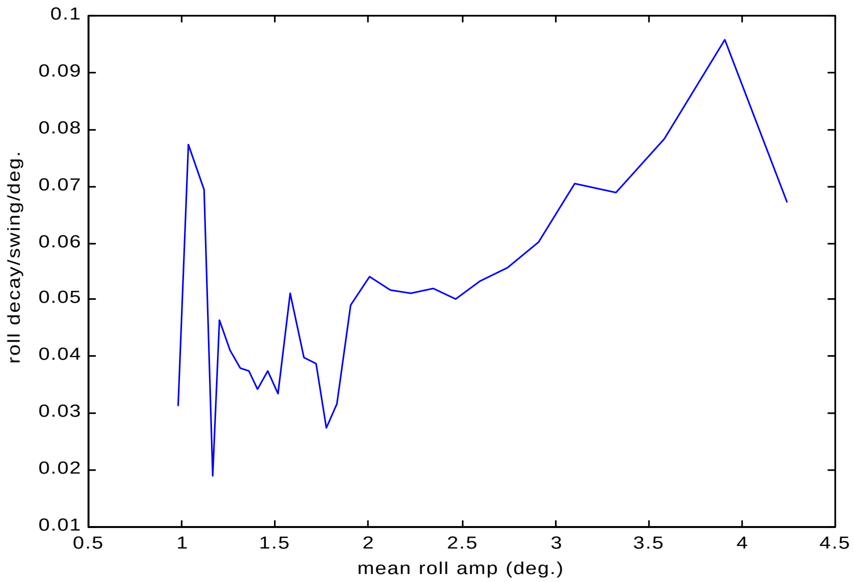

Figure 10-5. typical roll decrement curve run 11. 60 seconds

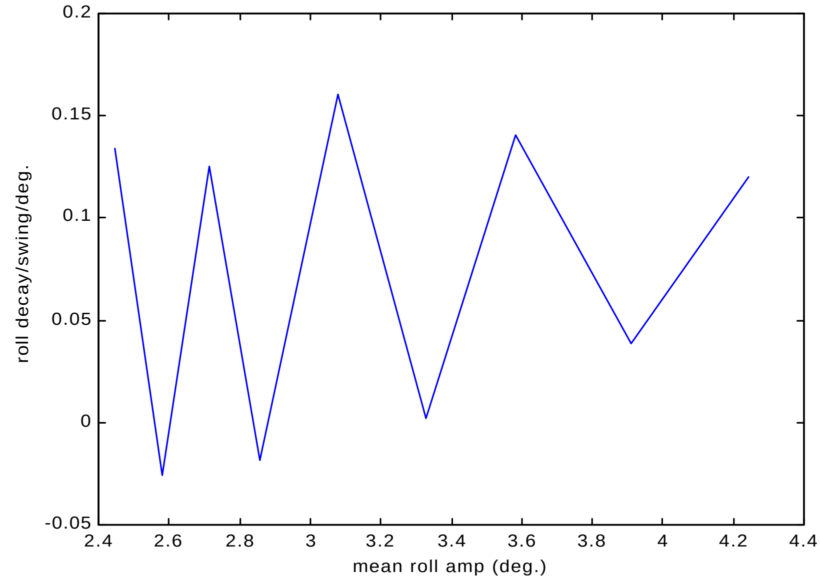

Figure 10-6. typical roll decrement curve run 11. 33 seconds

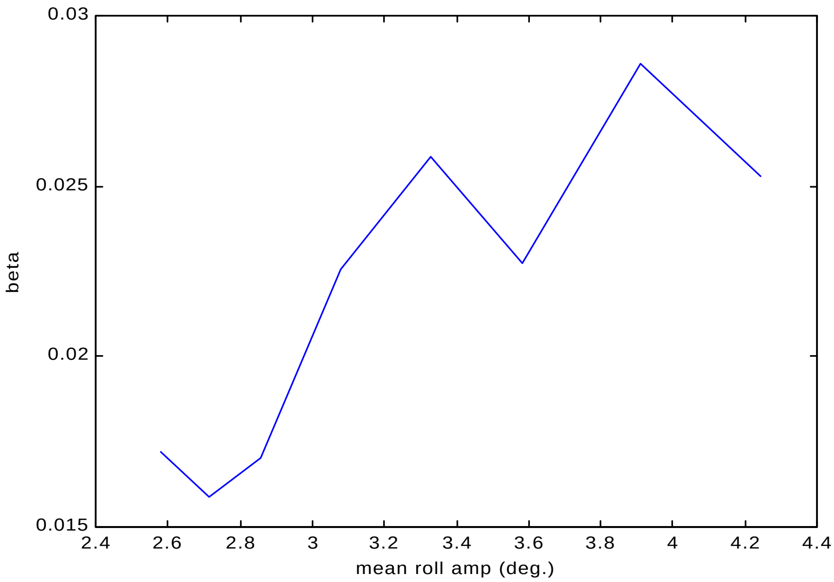

Figure 10-7. typical damping ratios run 11. 33 seconds

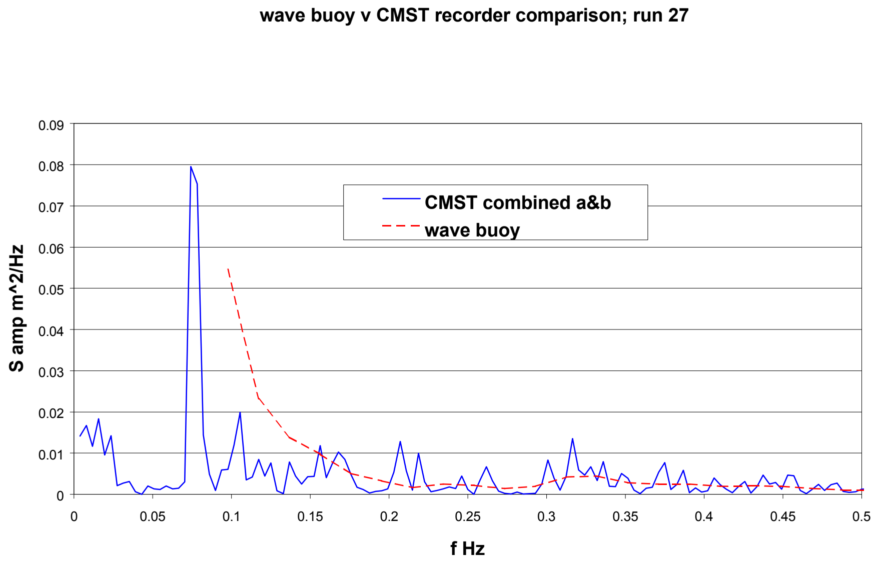

Figure 10-8. comparison of wave buoy with CMST recorders 28 June

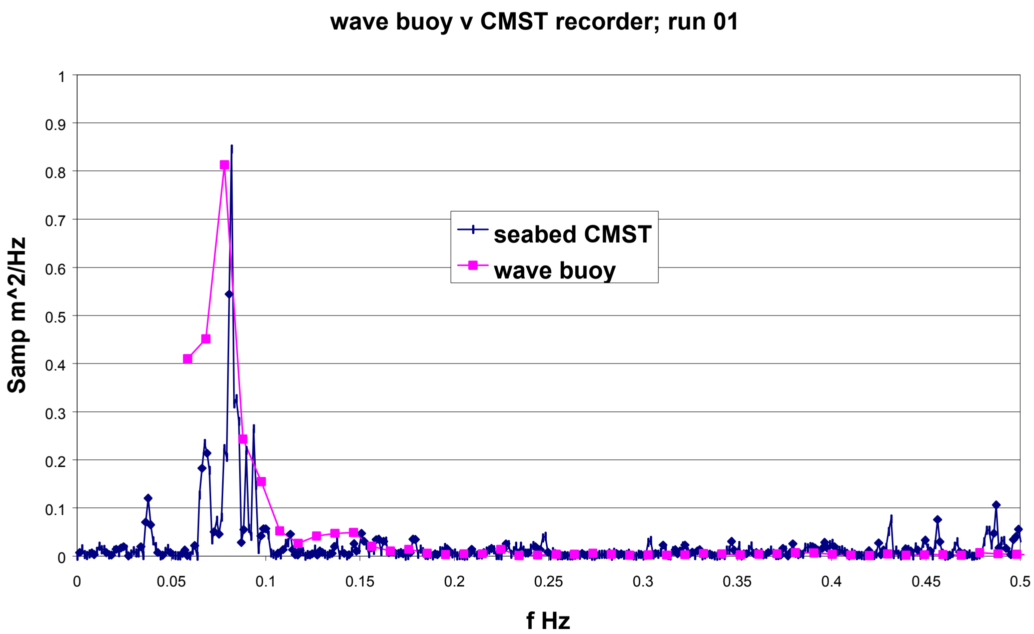

Figure 10-9. Comparison of wave buoy with CMST recorder 16 June

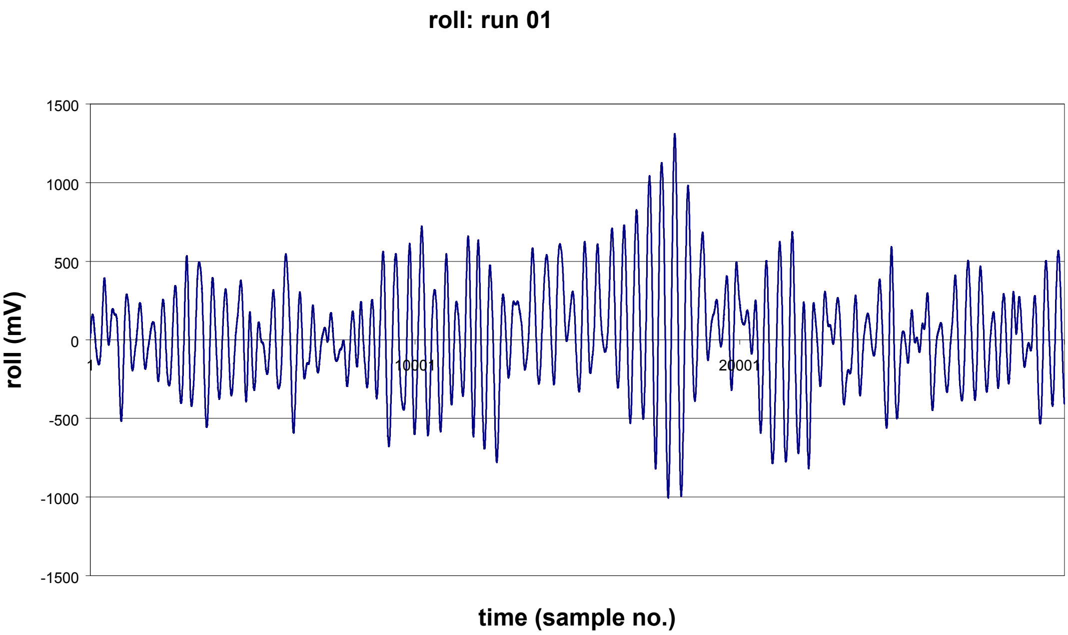

Figure 10-10. roll motion time series

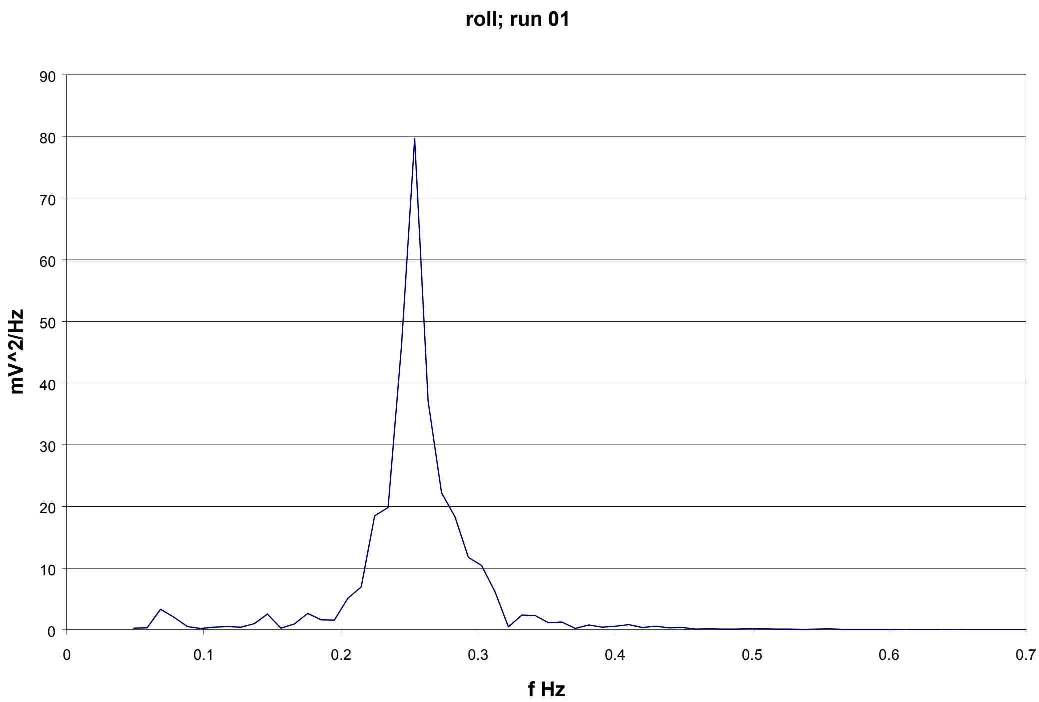

Figure 10-11. typical roll spectrum

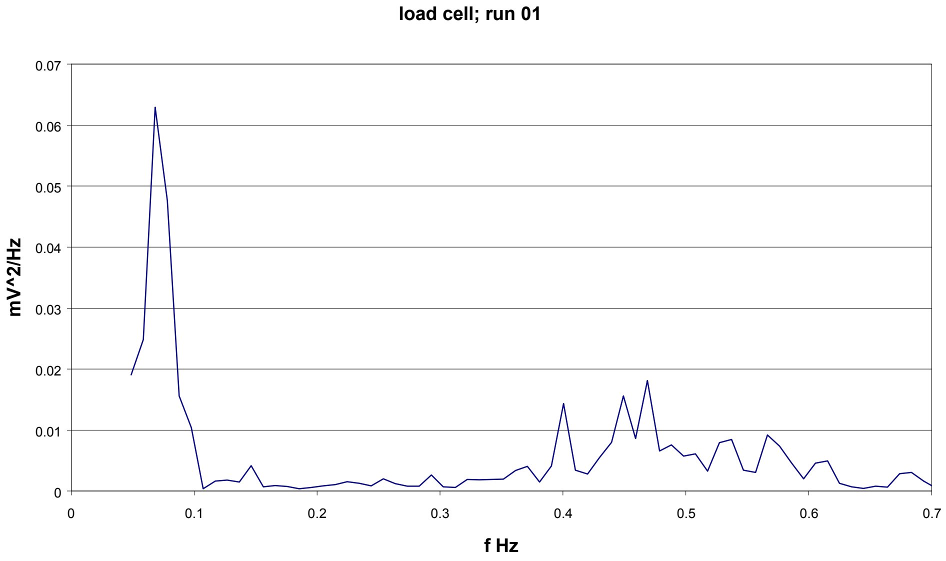

Figure 10-12. typical anchor load spectrum

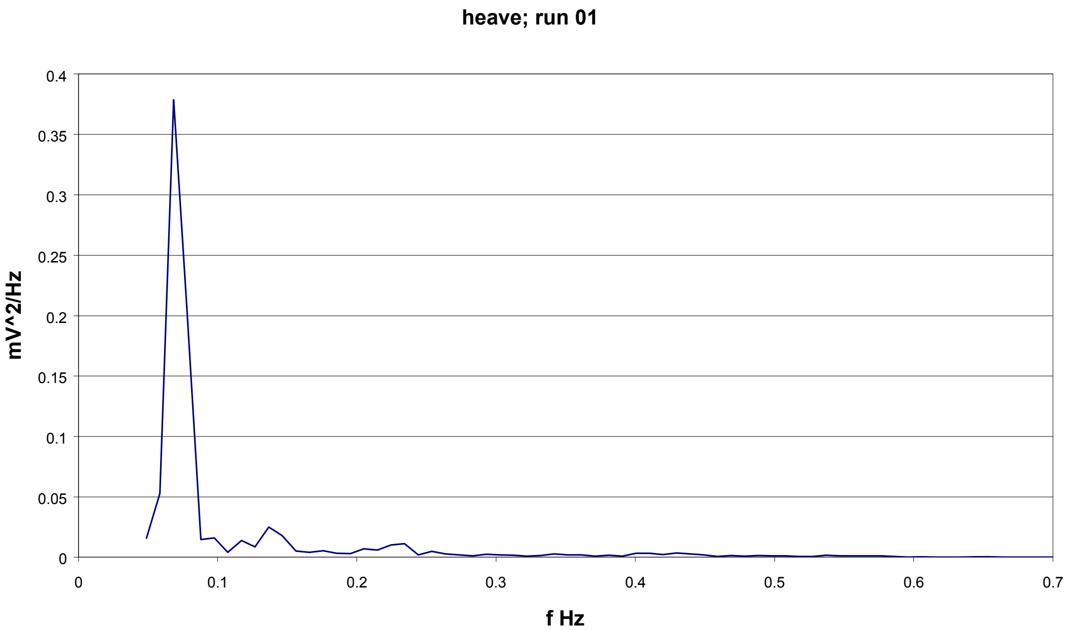

Figure 10-13. typical heave spectrum

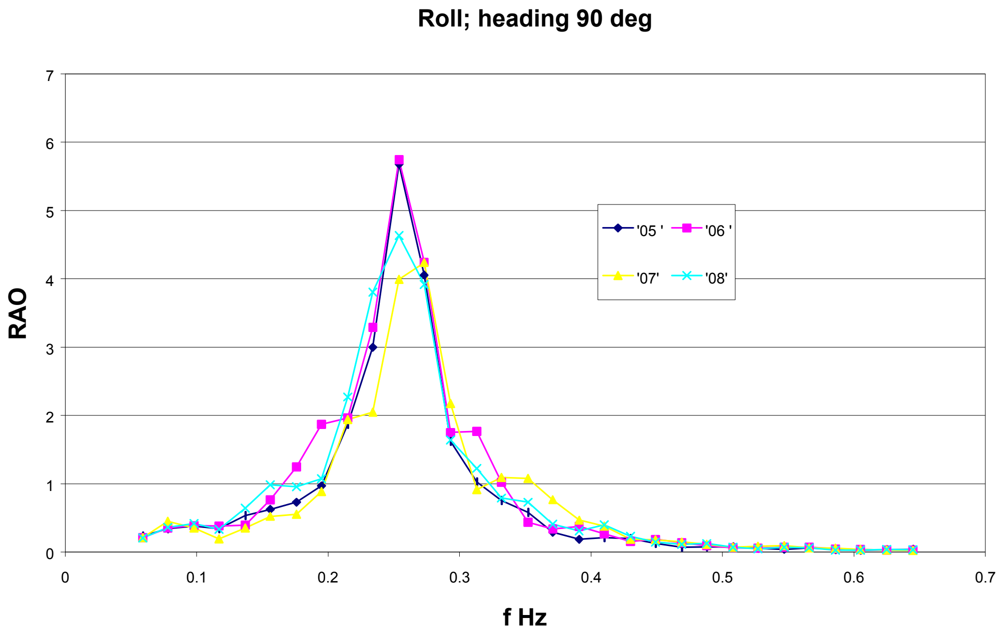

Figure 10-14. variation of roll RAO: 90 deg heading

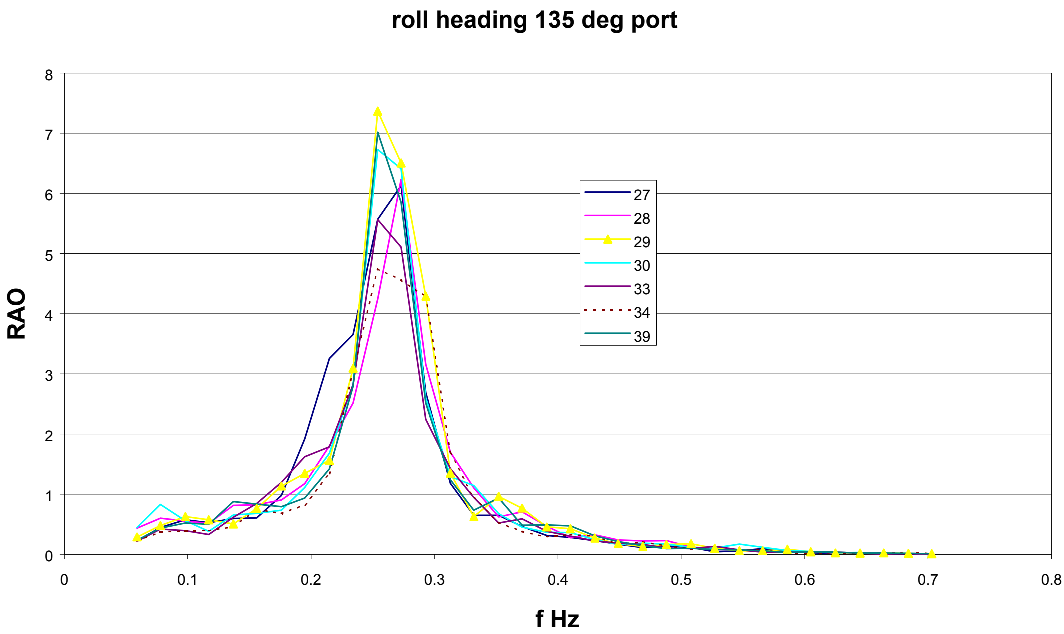

Figure 10-15. variation of roll RAO: 135 deg heading

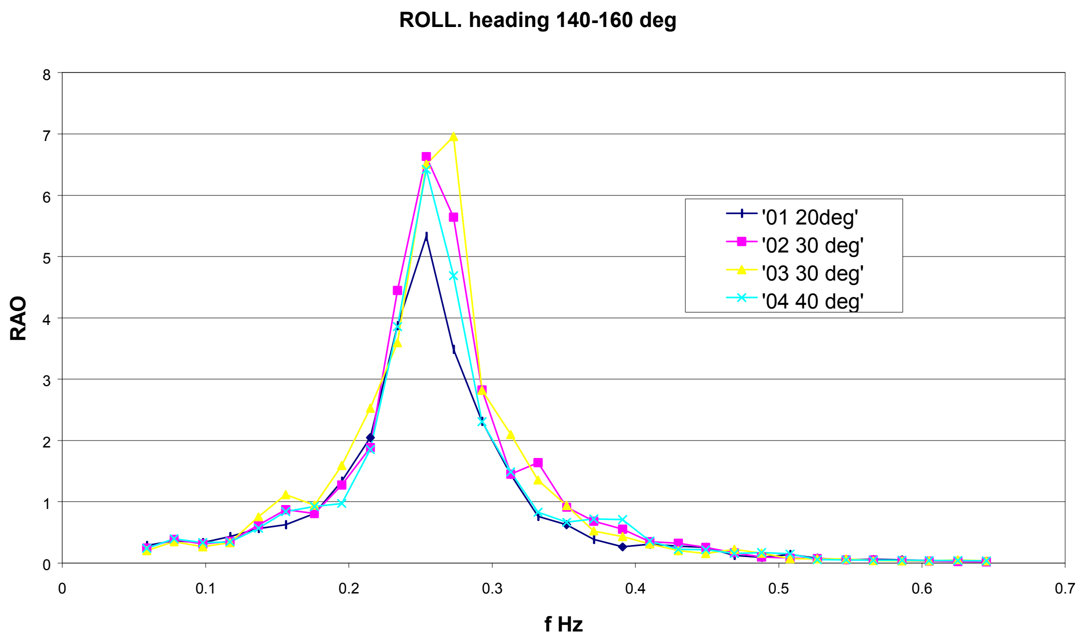

Figure 10-16. variation of roll: 150 deg heading

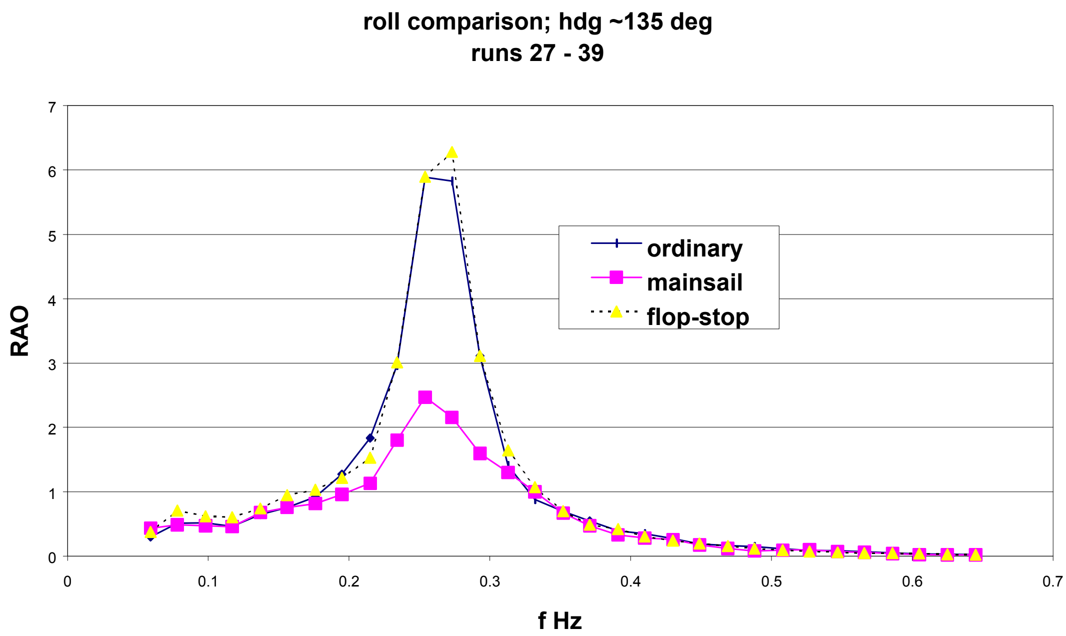

Figure 10-17. Effect of flopper-stopper and mainsail on roll

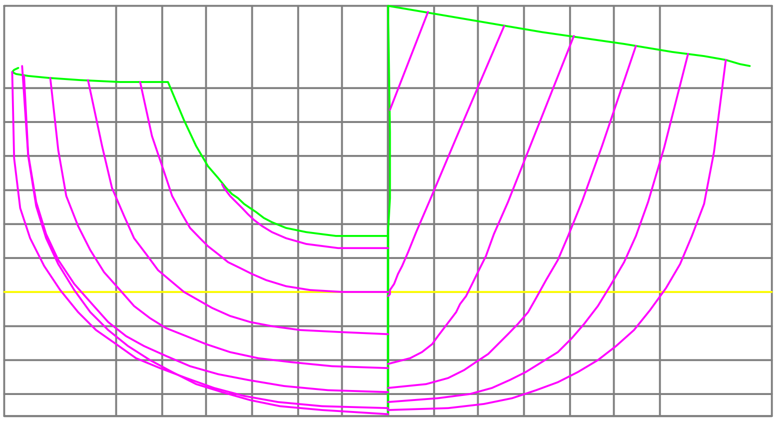

Figure 10-18. vessel body plan

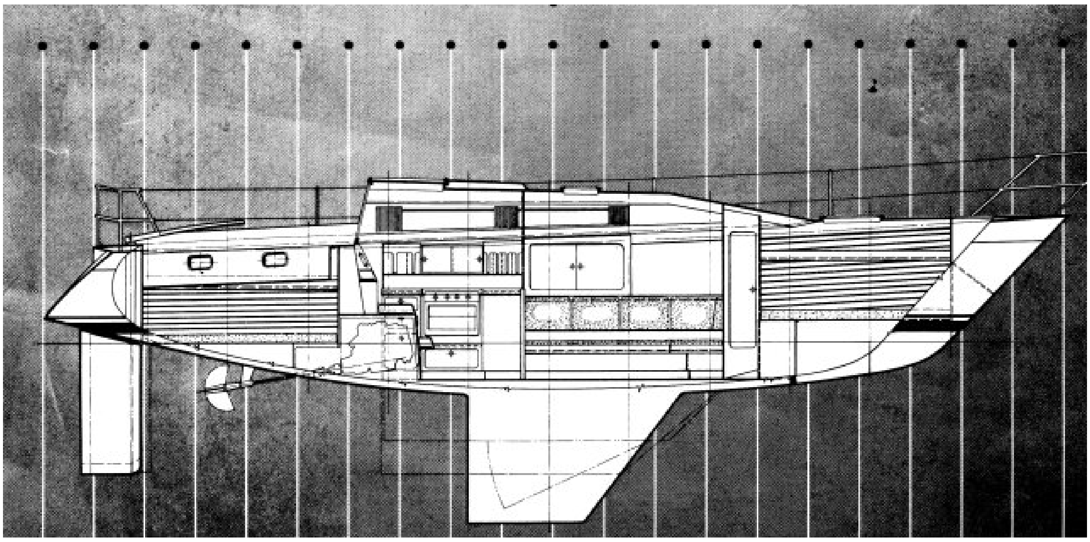

Figure 10-19. vessel profile

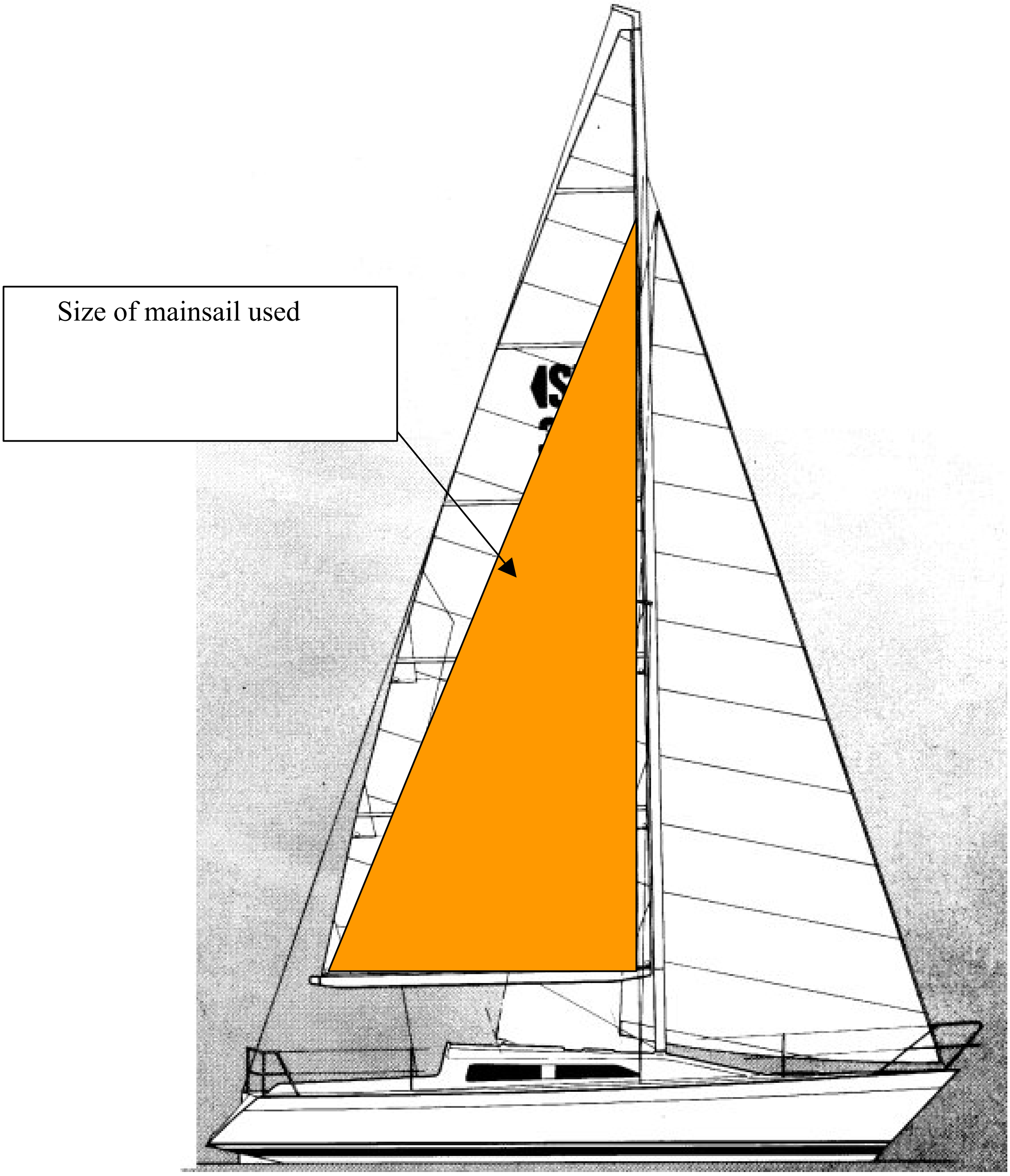

Figure 10-20. vessel rig

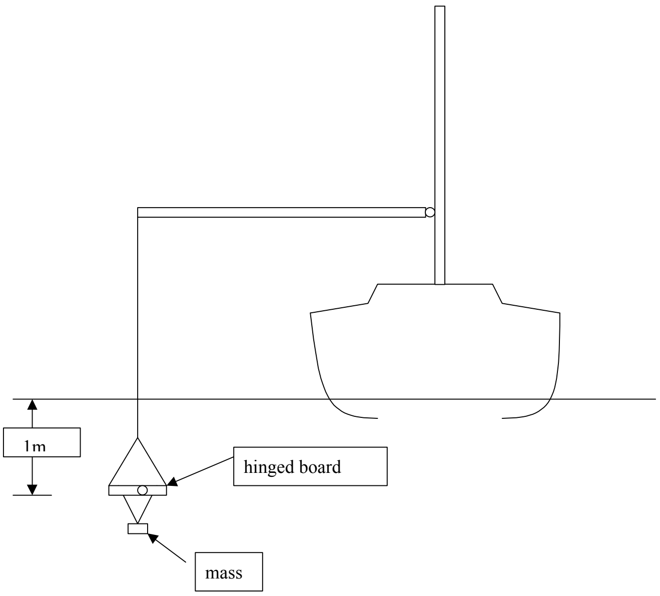

Figure 10-21 Flopper stopper deployment

11 TABLES

LOA (m)	10.34
LWL (m)	8.0
Bmax (m)	3.3
Draft (m)	1.85
Canoe body draft (m)	0.55
Mass (measurement trim) (Kg)	5442

Table 11-1Main vessel particulars

Luff (m)	9.60
Foot (m)	4.40
Leech (m)	10.33
Max. roach (m)	0.28

Table 11-2 Mainsail dimensions

item	Column no.	Raw calibration factor	Amplifier gain
Heave	1	1V/m	1
Roll	2	0.2V/m	1
Load cell	3	0.5mv/Kg	100
Pitch	4	0.2V/m	1
Wave buoy	5	258mV/g	10

Table 11-3Data acquisition settings

date:	28/06/00		**vessel:**	Panache II	**fbd bow**	**fbd P aft**	**fbd S aft**	
location	FSC works jetty		**project no**		1.25	0.918	0.908	
		longl pos (m)	vert pos (m)	transv (m)	*fbds with crew in dinghy			
		from bow	**above wl**	**+ port**				
tanks								
					mass Kg	litres max		
fuel 1		7.5	0.5	-0.6	**25**	40		
water p		6	0	0.6	40	150		
water s		6	0	-0.6	40	150		
bilge		6	-0.3	0	1			
other f.s.		8	0.5	0.6	1			
ground tackle						length	mass/m	
main anchr		0	1.3	0	16			
main cable	8mm@1,5	1	0.3	0	60	40	1.5	
2nd ancr					0			
2nd cable		8	0	-0.5	15	10	1.5	
3rd ancr		10	0.4	0	16			
3rd cable		10	0.4	0	15	10	1.5	
		longl pos (m	**vert pos (m)**	**transv (m)**	**mass**			
		from bow	above wl	+ port	Kg			
crew	**name**							
1	kim	7	0.6	0.7	72	nav statio		
2	cedric	8.5	1.5	0	70	mid-cockpit		
3								
4								
stores								
food cans1		4	-0.2	0.8	30			
food cans2								
bottles		5	0.3	0	10			
rig								
runners				0	0			
checkstays		7			3			
main		6	2.2	0	10			
headsail		1.5	5	0	10			
spi poles		2.6	1.1	0	15			
other								
dinghy		3.6	1.5	0	25			
outboard		9.7	1.5	0.7	3			

Table 11-4. vessel condition for inclining

Run no.	Start time	Vessel hdg	Wave dir	Wind speed (m/s)	Wind dir	Test condition
18	1004					Noise check
19	1030					Port datum
20	1033					Port inclined
21	1039					Repeat 19
22	1045					Repeat 20
23	1106					Stbd datum
24	1112	040		2.6	040	Stbd inclined
25	1114					Repeat 23
26	1120					Repeat 24

Table 11-5 Inclining experiment runs

	Heel angle (degrees)
Port (run 20 –run 19)	0.938
Port (22 – 21)	1.118
Stbd (24 – 23)	0.926
Stbd (26 – 25)	0.989
Mean	1.009
Standard deviation	0.118

Table 11-6 Inclining expt results

Run no.	Start time	Vessel hdg	Wave dir	Wind speed (m/s)	Wind dir	Test condition
10	0905					Noise check
11	0914					Free roll decay
12	0924	050		1.7	050	Repeat 11
13	0930					Repeat 11
14	0937					Main hoisted
15	0942					Repeat 14
16	0948			1.9		Repeat 14
17	0954					Repeat 14

Table 11-7 Roll decay runs

Run no.	k1	k2	β	Period (s)
11	.021	.017	.023	3.82
12	.011	.017	.025	3.78
12	.036	.007	.026	3.84
mean	.023	.014	.025	3.82

Table 11-8 Roll decay results: base condition 33 sec truncation

Run no.	k1	k2	β	Period (s)
14	.287	-.092	.060	3.80
15	-.198	.553	.094	3.46
16	.011	.144	.076	4.04
17	.061	.270	.084	3.98
Mean	.010	.219	.079	3.82

Table 11-9 Roll decay results: mainsail up 33 second truncation

Run name/no.	date	time	Duration (min)	Condition
Xtalk1	9/6/00		1	TSS signal, Educat PC
Xtalk2	9/6/00		1	Wave buoy signal, Educat PC
Xtalk3	9/6/00		0.5	Load cell signal, Educat PC
Bnoise2	9/6/00	1613	10	Lab, Educat PC
lapnoise	12/6/00	1416	0.5	Lab, Laptop PC
yotnoise	14/6/00	1434	5	On board in berth, laptop on battery
09	17/6/00			On board in berth, laptop on 12V ship supply
10	28/6/00	0905	1	At works jetty, pre-decay tests
18	28/6/00	1004	1	At works jetty, pre-inclining expt

Table 11-10. Noise checks

Run no.	Start time	Vessel hdg	Wave dir	Wind speed (m/s)	Wind dir	Test condition
01	1255	035	015	1.0	045	basic
02	1312	045	000			Repeat 01
03	1318	045+-20				Repeat 01
04	1324	055				Repeat 01
05	1344	105	015	2.4	000	Roped across waves
06	1352					Repeat 05
7	1358					Repeat 05
08	1404	100				Repeat 05

Table 11-11 Irregular wave runs: June 16

Run no.	Start time	Vessel hdg	Wave dir	Wind speed (m/s)	Wind dir	Test condition
27	1336	335+-5	292+-3	4.5	320	Basic (Anchored across waves)
28	1353	340	293	4.2	305	Repeat 27
29	1404					
30	1410					
31	1421	325+-15	296	4.4	315	Main up
32	1427	330+-30				Repeat 31
33	1449	335+-5	292	3.6	305	Repeat 27
34	1455	335				Repeat 27
35	1515	335+-5		1.7		Flopper stopper
36	1521	332				Repeat 35
37	1528					Repeat 35
38	1535	335	295	1.0	295	Repeat 35
39	1546	332				Repeat 27

Table 11-12. Irregular wave runs – 28 June

date	time	Height (m)
16 June 2000	0028	0.76
16 June 2000	0830	1.17
16 June 2000	1819	0.61
28 June 2000	0701	1.10
28 June 2000	1615	0.69

Table 11-13. Tidal heights. Source: DoT WA website

	Hs (m)	Tmean (sec)
sea	0.6	5
swell	1.5	12
total	1.8	10

Table 11-14. Rottnest wave data 1200hrs 28 June 2000. Source: DoT website

	Hs (m)	Tmean (s)
sea	0.4	4
swell	0.6	12
total	0.7	8

Table 11-15. Cottesloe wave data 1200hrs 28 June 2000. Source: DoT website