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IDENTIFICATION OF INFLUENTIAL PARAMETERS IN A SHIP'S MOTION RESPONSES: A ROUTE TO MONITORING DYNAMIC STABILITY

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SUMMARY

Six degrees of freedom motion response tests of a Ro-Ro model have been carried out in irregular waves under intact conditions. A stationary model was tested in different sea states for following, astern quartering and beam seas. The investigation was limited to the effect of encountered frequency components and associated magnitude of energy of the ship's motion responses. Analysis of heave, pitch and roll motions confirmed the vulnerability of the model to certain frequency ranges resulting in an adverse effect on the responses, and these were closely related to its natural frequencies. It was confirmed that the roll motion maintains its highest oscillation around the natural frequency in all sea conditions regardless of heading angles. However spectral analysis of the heave and pitch responses revealed the wave peak frequency. Roll is magnified when the peak frequency of wave approaches the natural roll frequency; therefore keeping them apart avoids a large motion response. It was concluded that peak frequency and associated magnitude are two important inherent characteristics of motion responses. Detection of influential parameters of encountered wave through heave and pitch responses could be utilised to limit a large ship's motion at sea.

1. INTRODUCTION

Stability is the ability of a ship to maintain an upright position and is one of the most important requirements for safe operation of a ship, as insufficient stability can lead to the capsizing of a vessel and the loss of life and property. For safe operation it is essential to maintain adequate stability during all operational and loading conditions. Ships sail in adverse weather conditions are likely to encounter various kinds of dangerous phenomena. Severe motion of a ship can cause damage to the cargo, equipment and people on board. The sensitivity of a ship to dangerous phenomena will depend on the actual stability parameters, hull geometry, ship size and ship speed.

Motion responses of a ship are an attractive method of assessing and comparing the performance of ships in rough weather. Ship motions and the waves encountered are recorded simultaneously and are analysed using spectral analysis techniques. However, the waves are irregular and without an accurate technique for recording them, the results obtained are unreliable estimates of the sea state. This becomes even more complicated when the ship is underway and the frequency of encounters changes.

This paper demonstrates that some influential parameters of encountered waves can be detected through the monitoring of heave and pitch motions. Because of a strong coupling nature, these motions are in tune with irregular wave patterns and therefore their responses can be regarded as applicable tools for the detection and estimation of influential wave parameters.

Out of ship's dynamic responses the roll motion has attracted the attention of many investigators and a number of regulatory bodies. Synchronous rolling and high roll motion are two potential dangers facing a ship's stability and can be avoided by taking appropriate action in ample time.

This paper also shows that the peak frequency of an irregular wave and the associated magnitude are the two most influential parameters on roll motion which can be measured by monitoring the heave and pitch motions.

1.1 REVIEW OF RECENT INVESTIGATIONS: THE OPERATIONAL POINT OF VIEW

Stability criteria are based on specific parameters of a vessel. The relationship between these parameters and the actual phenomenon is empirically derived from experience of operation, model tests, numerical simulations or from engineering considerations.

Over time, methods have been developed for the assessment of stability criteria [4] and these can be classified as:

- Statistical characteristics for restoring moments in waves
- Statistical characteristics of the metacentric height (GM) and other elements of the righting moment as a stochastic process
- An energy balance based method for evaluation of the probability of capsizing
- Effective wave with random amplitude
- Critical wave to evaluate the probability of capsizing
- Effective wave approach with up-crossing theory

However, these methods are mostly in the form of criteria applicable at the design stage rather than during the operational stage, and there is a distinction between safety measures to prevent capsizing during the designing of a ship and measures for the safe operation of a ship.

Over the past two decades, significant progress has been made in predicting ship dynamics and its application to ships, advanced model testing techniques, and computational methods [3]. However, several limitations and deficiencies in these techniques, such as uncertainty in defining the no return threshold or defining the level of safety and reliability, or inadequate simplifications, have rendered the results not always successful [8].

To help the ship's master take appropriate action in response to potential danger, guidance charts on a ship's expected responses have been proposed [17]. Various studies investigating the dynamic behaviour and survivability of intact ships have been conducted, including those by Hutchison [9], De Kat *et al.* [5], Rainey and Thompson [23] and Papanikolau and Gratsos [22]. However, very little attention has been paid to evaluating the responses of a vessel in calculating the stability parameters using the current International Code on Intact Stability (IS Code), as data concerning stability available to the ship's operator is generally still based on a ship's hydrostatics.

It is evident from the latest regulations, implementation, subdivision and stability that the rules are slowly moving from a deterministic environment to a probabilistic one also taking into account the presence of waves. It was emphasised in IMO [11] that a range of sea conditions should be taken into account when developing an instrument for evaluating the effect of a ship's design parameters on ship safety in a seaway. In line with this, the International Towing Tank Conference (ITTC) 2005 [15] considered specific operational aspects when evaluating the safety level of a ship. The evaluation should consist of a series of specified physical tests for given scenarios and environmental conditions.

In addition, the human factor is an important element of the ship stability system [16]. Recent analysis of 364 stability incidents identified the human factor as most important contributor [19].

According to Francescutto [8], intact stability criteria fulfil the design purposes by and large but to assure absolute safety, attention should be more focused on operational measures. "To assure safety only by inbuilt features is unfeasible; no ship could be built which cannot be capsized by negligence or bad operation" [7].

The Maritime Safety Committee in 1995 published "Guidance to the master for avoiding dangerous situations in following and quartering seas". This was developed with a view to providing masters with a basis for decision making regarding ship handling in following and quartering seas, thus assisting them to avoid dangerous phenomena that they may encounter in such circumstances [10]. The guidance was later revised in 2007 [13]. The initial concept of this guidance was to simplify the qualitative nature on which ships are dependent; however, the application of this guidance by the seafarer is difficult due to the following reasons:

- The limited familiarity of navigating officers with hydrodynamic approaches
- The omission of rare dangerous phenomena from routine checks means they could be easily missed
- Uncertainty in the method of approach to measurement of wave length and wave period

Compliance with the recommendations would however, promote the safety of a ship in a seaway.

A reliable, easily applicable method is essential to alleviate the dangers of a following, quartering, beam and head sea and such a method should avoid any manual computation. One solution is to address the ship's stability, in particular from the operational point of view. Operational stability is very complex but one important task is to explore the links between the sea state and the ship's course.

It is obvious that in dealing with online stability issues, the key factor is the sea state which should be addressed in the assessment of intact stability.

1.2 PERFORMANCE-BASED CRITERIA OF INTACT STABILITY

At the 48th session of the Stability, Load lines and Fishing vessel safety (SLF) Sub-Committee of the IMO, phenomena in seaways were identified which may cause large roll angles and accelerations, thereby placing ships at an increased risk of encountering critical stability situations. Three distinct physical phenomena responsible for stability failures were defined [12]:

- Righting lever variation
- Resonant roll in the dead-ship condition
- Broaching and other manoeuvring related phenomena

In response to potential dangers of seaways, one of the issues which was discussed extensively when revising the IS Code in 2002, was the development of "performance based" or "dynamics-based" criteria to predict stability failures. Intact stability criteria can be defined as either parametric or performance based and both can be either deterministic or probabilistic. In the current IS Code, prescriptive and parametric criteria are formulated in such a way that specific parameters must be greater than a certain quantity.

In a performance based approach by Kobylinski [18], the inherent characteristics of a physical model were analyzed in a set of predefined environmental and operational scenarios. These results were then used to calculate or measure the performance of the ship in terms of sufficient stability. Therefore performance oriented criteria based on a physical model is an option that can be used to address failure modes rather than via parametric criteria based on the measurement of a quantity related to the phenomenon [20].

In the 51st session of the SLF IMO sub-committee, the working group was instructed to consider new sets of criteria for application on certain ship types that could be considered more susceptible to hazards and to assess their value as “vulnerability criteria” [14]. Vulnerability in a ship’s stability is defined as “being susceptible to the adverse effect of environment and in particular the extreme motion behaviour”. However, it would be helpful if such criteria were based on physical considerations and could therefore be applied to any type of vessel [3]. Recently, vulnerability has been defined on two levels; the geometry of the ship, and its dynamic stability behaviour [4].

The revised 2008 IS Code came into force on 1st July 2010 and a review of this is still under consideration. However, in this new approach there are no clear indications of how to proceed in order to address the three modes of stability failures.

1.3 AIMS AND OBJECTIVES

Accurate calculation of changes in stability in response to waves presents certain challenges. The motion behaviour of ships in an environment characterized by waves and wind varies according to the different types encountered and this adds to the complexity of the dynamic responses when at sea.

The aim of this paper is to attempt to avoid high roll angles and hence excessive reductions of stability over long periods of time which increases the probability of capsizing. It is the authors’ opinion that detection of peak frequency of motion response and its corresponding magnitude in time can be a practical solution to monitoring the vulnerability of ships in different seas and operating conditions.

The objective of this paper is to develop a new method to analyse the sea state via the ship’s motion responses. Peak frequency of irregular waves encountered can be detected by the spectral analysis of heave and pitch motion over time. The paper also intends to evaluate the sensitivity of the roll response to ranges of encountered peak frequency close to the roll natural frequency as depicted in Figure 1.

An experimental approach was chosen for the development of practical tools to deal with the problem of dynamic stability in waves. Monitoring the behaviour of the motion response was demonstrated to be a good performance indicator for identifying development of a ship’s vulnerability to stability failure. The method is equally applicable to both conventional and non-conventional ships.

The stability status changes during operations and decisions taken regarding stability should not rely solely on the experience of the master. It is important to be aware of a developing critical situation that could result in the stability condition deteriorating, thereby maximising the time available to take corrective action by means of altering the course and/or speed.

While it is recognised that course and speed have direct effect on the encountered frequency but among those the change of course has the rapid and effective impact on encountered frequency.

In this study a Roll-on/Roll-off (Ro-Ro) model ship was used because of its vulnerability to greater stability losses which has been of great concern due to the large car deck spaces. Some of the main particulars utilised were from the previous work of Emin *et al.* [6].This paper presents the details and results of systematic motion tests performed with the Ro-Ro ship ‘‘Dextra’’ in irregular waves. The following sections of the paper detail the experimental set up, test conditions and measurements obtained. The measurements are presented and discussed in terms of peak frequency and peak power on the motion responses of the model.

2. DESCRIPTION OF THE EXPERIMENTAL SET-UP, TEST CONDITIONS AND MEASUREMENTS TAKEN

A range of significant wave heights and peak frequencies were chosen to develop a particular short-term sea state with a Pierson Moskowitz (PM) sea spectrum. Experiments were carried out in the towing tank of the Newcastle University. This tank is 36 m in length, 4 m wide and has a water depth of 1.2 m. The experiments involved systematic measurements of six degrees of freedom (6DOF) motion responses of a stationary model in an intact condition for three different headings in irregular seas. Comparative observations of restorative motions were carried out for heave, pitch and roll.

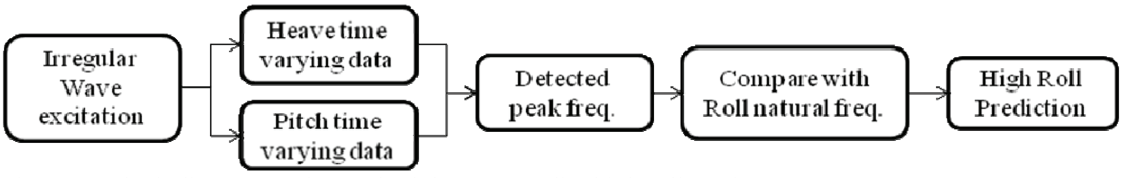

Figure 1: Block diagram of the methodology to predict high roll motion.

Figure 2: The Ro-Ro model in the towing tank with Qualisys marker in place.

In the experimental programme, waves were generated by a group of wave makers at one end of the tank and were absorbed by a parabolic beach located at the far end of the tank, which consisted of energy absorbing sheets.

The wave height and period were monitored and recorded using two wave probes and associated monitor. Qualisys Track Manager (QTM) with a ProRelex motion capture camera was used to track the motions of the model under different wave conditions and to process video data directly and convert it into coordinates. This system offers a quick way to obtain accurate 6DOF information compared with traditional methods using motion sensors attached to a model. Data output has 6DOF tracking which in every frame locates the position and orientation of one or more rigid bodies in the measurement volume. The data output is available and may be visualised as graphs on the monitor in real time. The Ro-Ro model with attached Qualysis marker in the floating condition is shown in Figure 2.

2.1 CONSTRUCTION OF MODEL

The study was carried out using a RO-RO ship for which model test data from previous experiments is available [6]. The main particulars of the model together with the prototype are given in Table 1.

Prior to the motion tests in waves, a set of free decay tests was carried out by manually forcing the model to respective motions and analysing the results to determine the average natural frequency. The roll decay of the model is presented in figure 3.

The model is constructed from fibreglass and is based on the offsets of a prototype Ro-Ro vessel [1][2]. The ship has a model ratio of 1:125 which is suitable for the size of the towing tank facility.

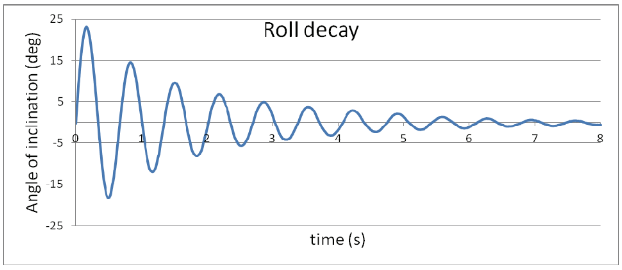

Figure 3: the roll motion of the model as a function of time.

The justification of the model scale can be summarised as follows:

- The length of the model tested in irregular waves at zero speed was just less than 1.5 m.
- The measuring instrumentation did not affect the behaviour of the model when encountering waves because there was no direct connection.
- The model was not equipped with a bilge keel. However, a lightly damped model performs large roll resonant behaviour which adds to the non-linear coupling effect on the heave and pitch motions.

Table 1: Main particulars of the Ro-Ro ferry and its scaled model

Particulars	Ship	Model (1/125)
Length overall (m)	187	1.496
Length between perpendiculars (m)	173	1.384
Breadth moulded (m)	26	0.208
Depth moulded (m)	15.7	0.126
Design draft (m)	6.5	0.052
Volume (m3)	16391	0.0084
Displacement) (N)	164800	0.08
Block coefficient	0.561	0.561
Prismatic coefficient	0.604	0.604
Midship section coefficient	0.929	0.929
Water plane coefficient	0.794	0.794
Height of metacentre above keel (m)	14.08	0.113
Height of centre of gravity above keel (m)	11.04	0.0897
Metacentric height (m)	2.86	0.0229
Longitudinal position of CoG from aft perpendicular (m)	78.73	0.636
kxx, Roll radius of gyration (m)	-	0.098
kyy, Pitch radius of gyration (m)	45.22	0.353
kzz, Yaw radius of gyration (m)	45.22	0.353

Model kyy and kzz were obtained from the DEXTREMEL report.

2.2 ACCURACY OF DATA COLLECTED

To ensure that the data collected from the wave probes matched with the desired output spectrum, test data was evaluated in the Wave Analysis for Fatigue and Oceanography (WAFO) environment [24].

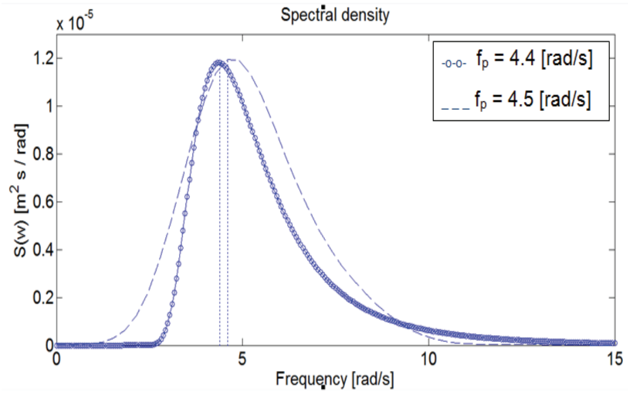

Figure 3: Comparison of Pierson Moskowitz sea spectrums developed by discrete time-varying data and WAFO mathematical modelling.

In Figure 3 the input signal to wave maker consists of a significant wave height (H_S) of 0.024 m and peak frequency of 4.4 rad/s. The spectrum output characteristic was compared against a mathematical model with a H_S of 0.027 m and peak frequency of 4.5 rad/s.

Although there is a slight discrepancy between the two curves shown in Figure 3, the motion responses were compared against characteristics of the generated spectrum, which is depicted as estimated frequency peak and power peak in the figures shown in the results in section 3.

In order to consider the influence of the nonlinear interactions between encountered, reflected, and radiated waves, the readings of the two wave probes were compared against each other. Although there was a slight difference in the output histogram, the variance and mean remained exactly the same for every test condition.

Prior to the experiments commencing, a matching calibration frame was used for the QTM in order to calibrate the measurement setup for optimum performance. The mass of the bare model was measured and then ballasted with weights to obtain an even keel. The required particulars as shown in Table 1.

The model was positioned 12 m distant from the wave makers with two wave probes placed between the model and the wave makers on the centre line of the tank. One probe was placed close to model and the other at a distance of 2.9 m. Transverse beams were located on the tank walls with studs attached to it in order to fasten mooring lines to the vessel. Mooring lines were connected to the bow and stern at the water level so that essentially the lines remained horizontal. Each line was comprised of a number of low stiffness tension springs connected to a nylon line and was fastened to the studs.

In this manner the vessel was maintained on station without preventing freedom of motion for the entire test period. However, the model was subjected to wave forces which resulted in both lateral and longitudinal movement and was arrested by the mooring lines in tension. This inevitably affected the motions to some degree but was unavoidable without allowing the unmoored vessel to freely move in the tank due to the wave action.

Table 2: Experimental wave conditions

Peak Freqrequency (rad/s)		Significant wave Height, H_s (m)		Sea state
Model	Ship	Model	Ship	
4.37	0.39	0.024	3	Low
6.42	0.57	0.048	6	Medium
9.92	0.89	0.072	9	High

2.3 TEST CONDITIONS

The model was tested stationary in the intact condition. The total number of recorded runs was 27, which consisted of three peak frequencies, with three significant wave heights and three heading angles. The heading angles were 0°, 45° and 90° corresponding to following,

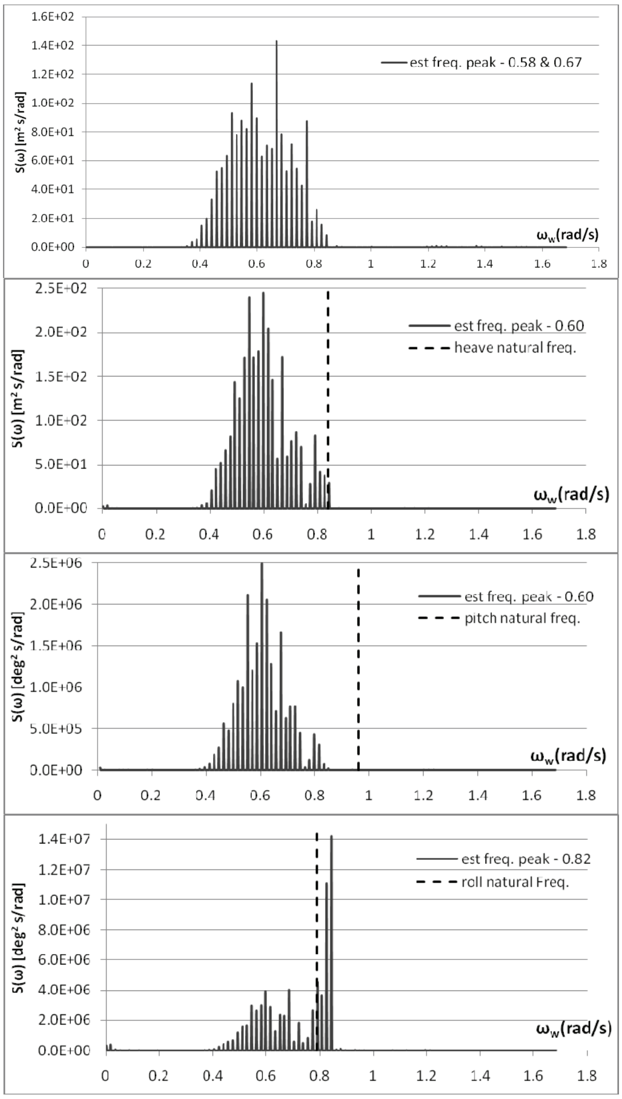

Figure 4: Full scale power spectral analysis of the wave, heave, pitch and roll motion

astern quartering and beam seas, respectively. Table 2 lists the intended spectrum characteristic applied to the wave maker to generate irregular waves. Due to the large volume of results obtained after analysis of each motion response, only a sample of the analysed power spectrum in the full scale condition is shown in Figure 4, based on the model peak frequency of 6.42 rad/s and Hs of 0.024 m.

Each test ran for eight minutes to avoid unreliable results and once the model has reached the steady state condition then motions were recorded. The wave conditions stated above were selected in order to maximise the possible test runs over a wide range of frequencies. The model was free from green water effects and the mooring lines did not apply excessive force to restrain the motions.

3. RESULTS

The discrete time-varying data of the motion responses and incoming waves were monitored by QTM and two wave probes respectively, and were recorded using LabVIEW software [21]. Recorded data was analysed using power spectral density (PSD), which describes how the power of a signal or time series is distributed with frequency. The time domain window selected was the Hanning type. LabVIEW and MATLAB environments were used for analysing the data obtained and the sampling rate for data acquisition was 100 Hz.

Prior to the start of the experiment, a set of free decay tests were performed. The model was manually forced to freely oscillate and the motion analysed by QTM to determine the average natural frequencies. The measured results were scaled to the full-scale values and are given in Table 3. However, since the model heave and pitch stiffness values are high, the decay curves had a limited number of oscillations and therefore the results may have a degree of uncertainty; consequently, the heave and pitch natural frequency is quoted from [6].

The figures presented in this section represent the motion responses of the ship; the x-axis presents the sea conditions (defined as 'low', 'medium' and 'high' for the three different peak frequencies utilised in generating the wave spectrum) and the y-axis is either estimated frequency peak (rad/s) or estimated power peak (deg^2 s/rad for pitch and roll, m^2 s/rad for heave). Respective motions have been scaled for ease of comparison. The results are presented for the three values of H_S and these are defined as 'small', 'medium' and 'large' in association with the three different frequencies utilised in generating the wave spectrum.

Table 3: Predicted natural frequency of the ship

Particulars	Heave	Pitch	Roll
Natural frequency of ship ω_n rad/s	0.84	0.96	0.79

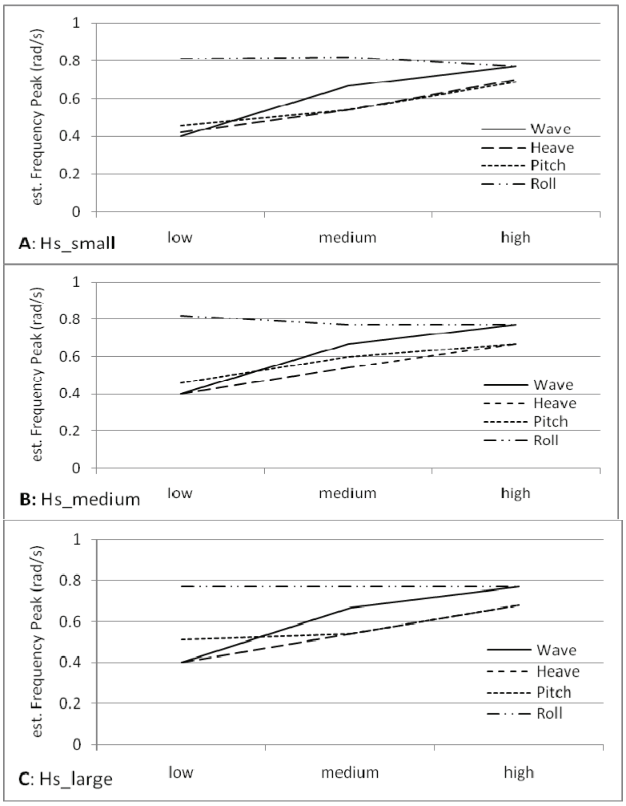

Figure 5: Comparison of peak frequencies for each sea condition tested in a following sea. a) small H_S b) medium H_S c) large H_S

In the following discussions, the main emphasis is on the effect of the estimated frequency peak and power peak on the motion responses and any other notable trends observed in the response curves.

3.1 MOTION RESPONSES IN A FOLLOWING SEA

As shown in Figure 5a, the response of pitch and heave motion are strongly coupled and closely follow the peak frequency of waves in different sea conditions. However, the roll motion maintains a response close to its natural frequency.

A similar trend can be observed in Figures 5b and 5c where the value of H_S is increased. However, the coupling effect of heave and pitch under low sea conditions is not as strong as in high sea conditions and it appears to be less significant at a medium H_S value. The roll response remains pretty constant for every sea condition and H_S value tested.
The changes in heave and pitch magnitudes shown in Figure 6a are in line with changes in wave magnitude. However, roll magnitude does not display a distinct refraction and follows a steady trend with a slight decrease at high frequencies.

The rate of roll motion response increases in the higher sea state where the range of wave peak frequencies is

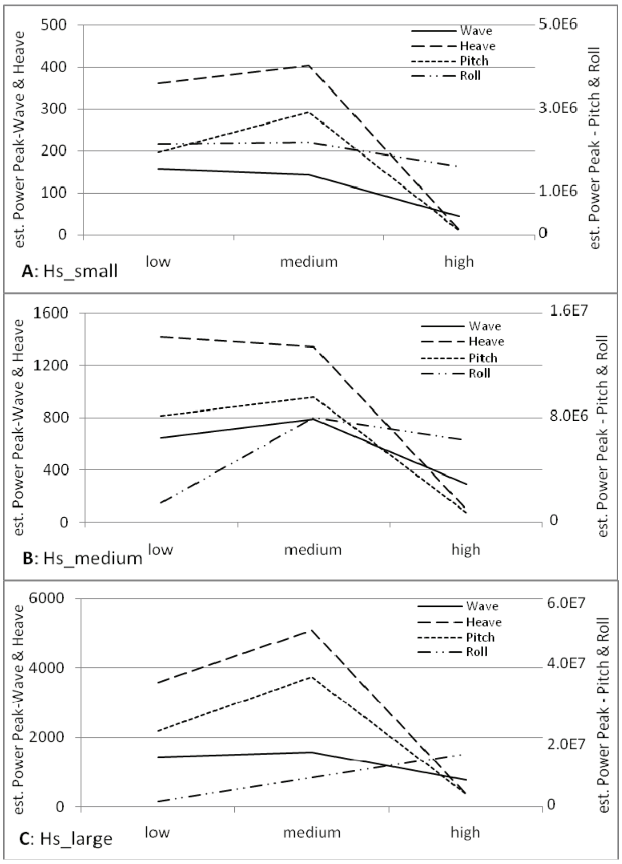

Figure 6: Comparison of energy magnitudes for each sea condition tested in a following sea. a) small H_S b) medium H_S c) large H_S

closer to the natural roll frequency and it reaches its maximum at the large H_S value. The coupling effects of heave and pitch motions are obvious in all sea conditions and at every H_S value tested and their magnitude remains high except when at high frequencies.

3.2 MOTION RESPONSES IN AN ASTERN QUARTERING SEA

The results in an astern quartering sea are interesting because a change of sea direction from stern to quarter has less effect on peaks frequencies of motions in comparison with Figure 6. The coupling effects of heave and pitch motions are similarly maintained throughout the change in heading angle (These are not presented due to the large volume of results).

The trend in changing amplitude as depicted in Figure 7 is complimentary and corresponds with roll responses in a following sea. The magnitudes of heave and pitch reach their maximum in medium sea conditions.

3.3 MOTION RESPONSES IN A BEAM SEA

The strong couplings amongst motion responses are dominated by roll and heave motions around roll natural frequency. The pitch motion response tracks the wave peak frequency but being less sensitive at low sea condition.

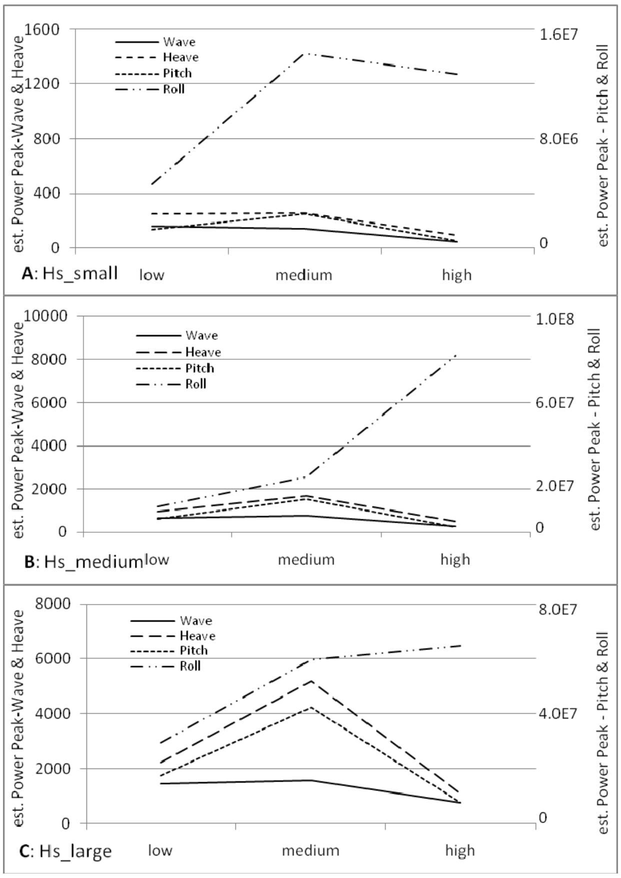

Figure 7: Comparison of energy magnitudes for each sea condition tested in an astern quartering sea. a) small H_S b) medium H_S c) large H_S

The magnitudes of the motions are scaled in Figure 8 and the trend observed is a good indication of the coupling effects being dominated by the roll response in beam seas.

Figure 8 verifies that the rate of roll response remains high when the encountered peak frequency is close to the natural frequency.

It was observed that the roll motion maintains its highest oscillation around the natural frequency in all sea conditions regardless of the heading angle. Roll is magnified when the peak frequency of the wave approaches the natural roll frequency; therefore, keeping these apart avoids a large motion response. Alteration of course away from a beam sea improved the roll motion.

3.4 ROLL RESPONSE IN ALL SEA CONDITIONS AT DIFFERENT HEADINGS

Frequency ranges of the generated wave spectrum increased towards higher sea conditions. It is apparent that wave energy has to decrease at higher frequencies.
Roll responses are directly related to the ratio of wave peak frequency to natural frequency. Figure 9 shows that the maximum responses occur around unity which becomes nonlinear and wave energy has less effect on the power magnitude of roll motions. It also shows that

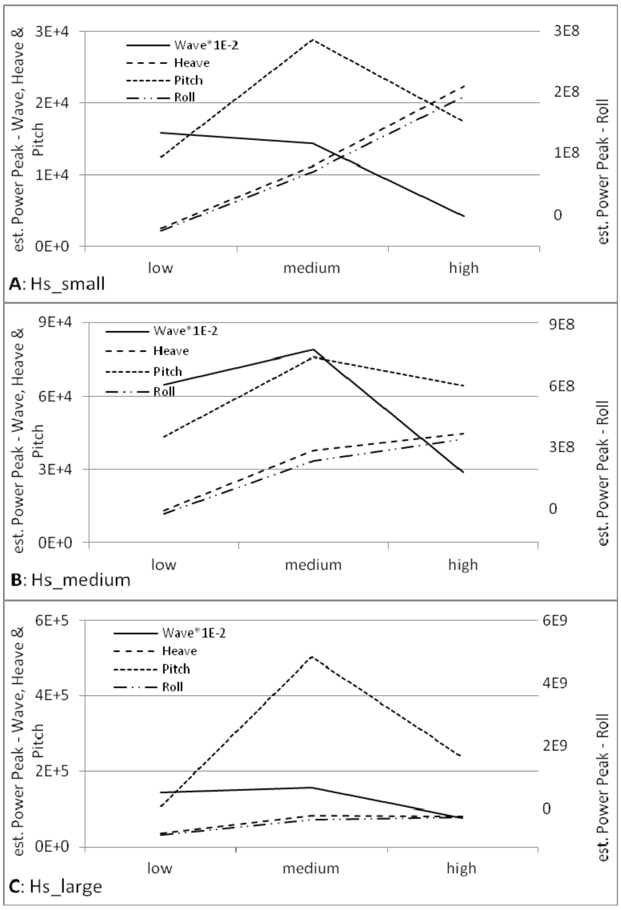

Figure 8: Comparison of energy magnitudes for each sea condition tested in a beam sea. a) small H_S b) medium H_S c) large H_S

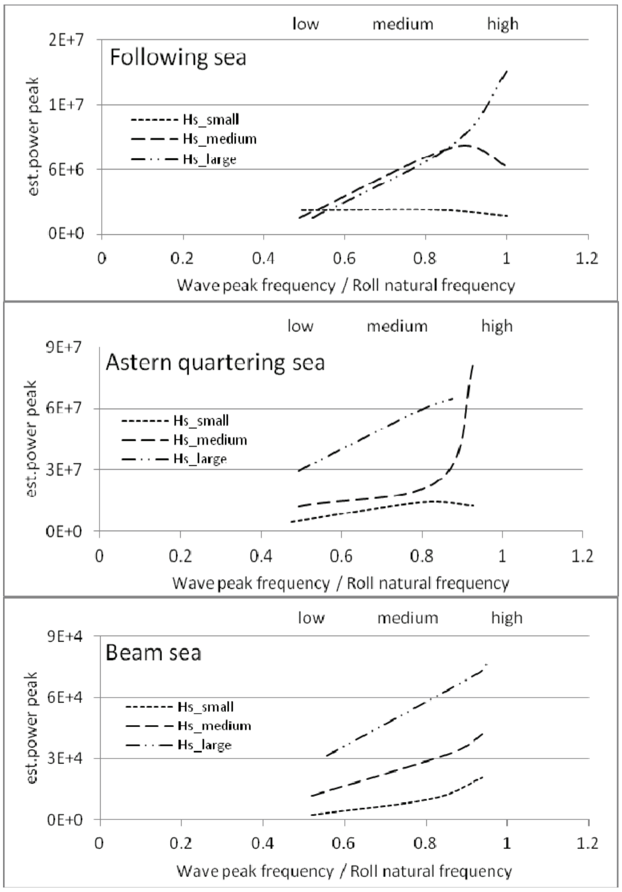

Figure 9. Roll responses under different operating conditions

the maximum power peak is obtained during beam seas and is reduced in following sea.

4. CONCLUSIONS

Motion response tests of a small-scale model of a Ro-Ro vessel have been performed in irregular waves under intact conditions. Six degrees of freedom motion responses of the stationary model were measured over nine different combinations of wave peak frequencies and significant wave heights in following, astern quartering, and beam sea conditions. Bearing in mind the main objective of exploring the effect of the encountered frequency and corresponding magnitudes on the model responses, the following conclusions were drawn:

- This study has found that heave and pitch motion responses in all heading angles do not display any distinct nonlinear trends with respect to changes of sea state. Motion behaviours tend to remain linear as clearly observed in the response curves, owing to a strong coupling effect. The only exception is heave motion in beam sea.
- One of the significant findings to emerge from this study is that the peak frequency of pitch motion tends to follow irregular wave peak frequencies for all headings. Heave motion also tends to behave similarly except in beam sea which couples with roll motion.
- Another major finding was that roll motion tends to oscillate around its natural frequency in all sea conditions and different heading angles and is sensitive to a limited range of encountered peak frequencies associated with the sea state which are close to its natural frequency.
- In the roll motion, distribution of the response energy is concentrated at the natural frequency.

An implication of these findings could be their use in enhancing the operation of a ship via the development of a tool to monitor and advise the navigator to take corrective action. Such a tool could:

- Evaluate the vulnerability of a ship to motion responses by detecting components of encountered frequency and their corresponding magnitude.
- Detect parameters that are used as performance indicators to warn of the development of a critical situation and hence a reduction in stability.
- Avoid large roll motions by alteration of course in ample time.

This paper has demonstrated that spectral analysis of heave and pitch responses can be used to identify irregular wave peak frequency and associated magnitude.

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