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Statistical Analysis of Compartment Permeability Influence on Damaged Ship Motions

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Abstract: The study shows the changes in heave and pitch motions when a ship hull is damaged with varying compartment permeability values using wave statistics. It is an experimental investigation into obtaining motion measurements of an intact and damaged frigate model in waves. Experiments were carried out using the Southampton Solent University towing tank facility and a 1/43.62 scale segmented frigate model of the Leander Class Frigates Hull. During the experiment wave length/wave height was kept constant whilst wave frequencies were varied from 3.173 to 6.276 rad/s. The tests were carried out with the model stationary and in motion with a forward speed of 1.4ms^{-1}. Results of the tests indicated that compartment permeability has a non-linear effect on heave and pitch motions of a damaged ship.

Keywords: Intact, Damage, Ship Motions, Compartment Permeability, Ballasted

1. Introduction

In the early days of shipping, research in the maritime industry was focused on building large size ships. This was to ensure the carriage of goods in large quantity. As shipping advanced, other areas of research such as propulsion machinery and lightweight structures for ship construction became important. Currently research focus is on structure integrity and hydrodynamics. This is due to the several loss of ships when damaged leading to the loss of lives and property. Damaged ships have dominated this area of research with the accent on the ingress water influence on the hydrodynamic behaviour (motions and loads) of ships when damaged. Factors such as air stiffness, damage size and location, compartment permeability and internal arrangement of cargo which affects the quantity of ingress water are been investigated.

Anon (2014) lists the worst cruise ship disasters recorded so far. The list includes the statistics of the number of passengers and crew on board, what caused the ship to sink, and the number of lives that was lost. From the statistics it is clear that damaged ships sustain holes in their hulls leading to flooding of the ship compartments and overloading of the hull. The damage (holes) are as a result of collision, grounding, raking, or weapon damage. This is structural damage and defined by Smith (2009) as any accidental modification or intentional harm to the ships as built hull condition. Meanwhile, due to the environment in which ships operate and the cargo stowed on board, they are subjected to loads and motions (Bai, 2003). This implies the floodwater on board damaged ships, subjects' ships to additional loads and extra motions.

Korkut, Atlar and Incecik (2003) investigated wave induced loads and motions on intact and damaged ships. Using both experimentation and numerical computations, results indicated difference in motion and hull girder loading between the intact and damage ships. Chan, Incecik and Atlas (2001) also investigated the performance of a damaged Ro-Ro ship in various sea states and concluded that the most critical condition is when the Ro-Ro ship is in quartering seas. Wood, Hudson and Tan (2009) using Computational Fluid Dynamics (CFD) simulations, observed that as damage size (area) decreases it takes a longer period to flood a damaged ships' compartment. Furthermore, Vredeveldt, Journee and Vermeer (2000) discusses the possibility of increasing the crashworthiness of a ship through reduction of the compartment permeability of the void spaces in the side hull. Similar to the works of Wood, Hudson and Tan (2009) and Korkut, Atlar and Incecik (2003), Smith, Drake and Rusling (2007) (as cited in Smith, Drake and Wrobel, 2009) investigated the magnitude of the structural loads experienced by damaged ships when the damage size and location are varied.

Following the recommendations of Smith, Drake and Wrobel (2009), Leblanc (2011) investigated the effects of compartment permeability and internal arrangement on the added mass and damping of a damaged ship section. This was an experimental investigation in which a ship model made from plywood was tested in a towing tank. The results show that the magnitude of both added mass and damping change significantly for the different compartment permeability values over the amplitudes and frequencies tested. On the other hand, internal arrangement configurations did not show much difference in added mass and damping. The outcome of the research is an indication that compartment permeability influences added mass and damping of a damaged ship. However, in Bishop and Price (1979) a correlation is seen between added mass, damping and ship motion. Hence the question to be answered is whether or not, compartment permeability has influence on the motions of damaged ships.

Also Leblanc (2011) findings and those of other researchers are based solely on the comparison of Response Amplitude Operators (RAO). But in Phelps (1995) it is explained that within a period of 20-30 minutes, a wave system at a particular point may be considered statistically stationary and wave statistical parameters such as wave amplitude, height, period and moments of the spectrum may be determined and used to quantify the severity of the motions experienced by the ship. This approach explains how the individual wave statistical parameters vary with ship loading or motions.

The current paper presents an experimental approach aimed at predicting heave and pitch motions for a sample frigate in intact and damage conditions. Only a one compartment damage scenario is considered, with empty 330 mml cans stowed in the compartment to achieve the various compartment permeability values of 100%, 80% and 70%. This paper focuses on correlating wave statistics results for the damaged cases in explaining the influence compartment permeability has on heave and pitch motions of damaged ships. The approach used in the study enhances data analysis by examining ship performance in respect of changes in the individual wave statistical parameters.

The paper is organized into four main sections, with the introduction followed by methodology in which the concepts, materials and equipment used for the study are described. This is followed quickly by the results section where the results of tests conducted are presented. Discussions and conclusion enumerates findings which lead to the realization of the purpose of the study. Finally acknowledgement and list of references are given.

2. Methodology/Methods and Materials

2.1. Overview of Methods Used

Physical experiments were conducted using a Leander Class Frigate Hull model tested in the Southampton Solent University (SSU) towing tank and data acquired for analysis. Experimental Response Amplitude Operators (RAOs) were then derived for intact and damage conditions, in regular waves at zero and forward speeds. In the damage condition, experiments were carried out at 100%, 80% and 70% compartment permeability (CP) values. Tests measured only heave and pitch motion responses of the model. Finally, the wave and motions amplitudes, heights, periods, frequencies and moments of the spectra were calculated in order to investigate statistically, the correlation between compartment permeability, and heave and pitch motions of a damaged ship.

2.2. Description of Equipment and Materials Used

The towing tank (as shown in Figure 2.1) is 60 metres long, 3.7 metres wide and has a water depth of 1.86 metres with a maximum carriage speed of 4.60 ms-1. It uses a single paddle wavemaker, driven by a HR Wallingford motor to generate waves.

Figure 2.1. *SSU towing tank facility.*

The waves were monitored using a resistance type wave probe, 0.42 metre in length and was attached to the towing carriage ahead of the model. Potentiometers were used in measuring the heave and pitch motions of the model. The model (shown in Figure 2.2) used in the study is a segmented ship model whose design and construction was based on the offsets of a sample ship of the Leander Class Frigates. The individual segments were joined by a flexible aluminium backbone beam running through the model longitudinally and the gaps between segments sealed using rubber membrane and masking tape. Principal particulars of the model and ship are given in Table 2.1.

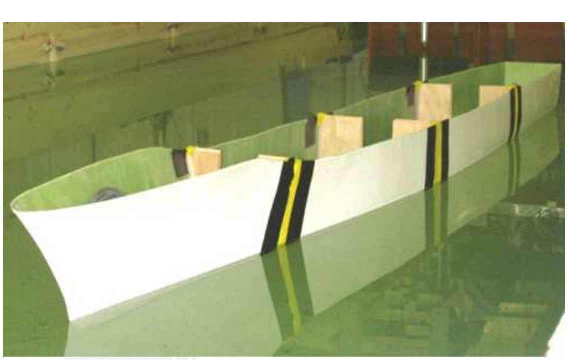

Figure 2.2. *Photograph of segmented ship model.*

Table 2.1. *Principal dimensions for model and ship.*

Main Particulars	Ship	Model
Length overall (m)	113.4	2.6
Length between perpendiculars (m)	109.72	2.52
Midships beam (m)	12.36	0.29
Midships draught (m)	4.19	0.096
Maximum draught (m)	4.36	0.1
Displacement (kg)	2921000	29.4
LCG aft of midships (m)	3.96	0.091
Service speed (knots)	18	1.4
Pitch gyradius	25.26	25.9

As the model had to be tested in damaged conditions as well as intact, an appropriate damage size had to be decided. A one compartment damage scenario was assumed and the model was damaged at the bottom of the third hull segment from the fore, with the damage size being 81.71 cm^2 as shown in Figure 2.3. By stowing 330 ml cans (as in Figure 2.4) in the damaged segment, compartment permeability values of 80% and 70% were achieved for the tests conducted.

Figure 2.3. *Damaged segment of ship model.*

Figure 2.4. *Photograph of 80% CP test.*

Through the heel fitting and toupost the model was connected to the towing carriage, which runs on rails during forward tests (shown in Figure 2.5). Filtering of the electrical signals from the potentiometers and wave probe was achieved using the Churchill box. Finally, data from tests were acquired digitally using a data acquisition system which comprised of a computer and the DaqView software.

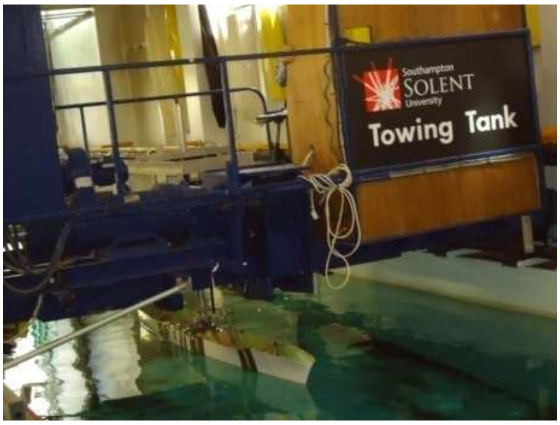

Figure 2.5. *Ship model fitted to the towing carriage via toupost and heel fitting.*

2.3. Description of Experimental Procedure

The model sea state was defined by six (6) wave encounter frequencies (shown in Table 2.2), one (1) wave height to wavelength ratio of 0.02, two (2) model speeds (0 and 1.4m/s) and regular head type waves.

Table 2.2. *Wave encounter frequencies.*

Model Frequency (rad/s)	Ship Frequency (rad/s)
3.173	0.480
3.305	0.500
3.701	0.560
4.361	0.660
5.215	0.790
6.277	0.950

Experimentation started with the ship model ballasted and then fitted to the towing carriage. Next the data acquisition system and wavemaker were started. For zero speed tests, the towing carriage was held stationary and ship model excited by the waves, and heave and pitch oscillations recorded at a sample rate of 100 Hz. On the other hand, for forward speed tests, towing carriage was moved at 1.4 m/s to depict model in motion, and again heave and pitch oscillations were recorded. Intact tests were conducted with the damage hole sealed whilst damaged tests were conducted with the seal taken off and the damaged segment of the ship model allowed to flood. In each damage test, the appropriate number of 330 ml cans was stowed in the damaged segment in order to realize CP values of 100%, 80% and 70%. Each test run ended, immediately the first wave approached the other end of the tank. And a period of twenty (20) minutes was allowed in-between tests.

2.4. Description of How Data Was Processed

The DaqView software displayed the acquired data in matlab as sinusoidal waves, with crests and troughs as shown in Figure 2.6. The crests and troughs are the heave, pitch and wave displacements.

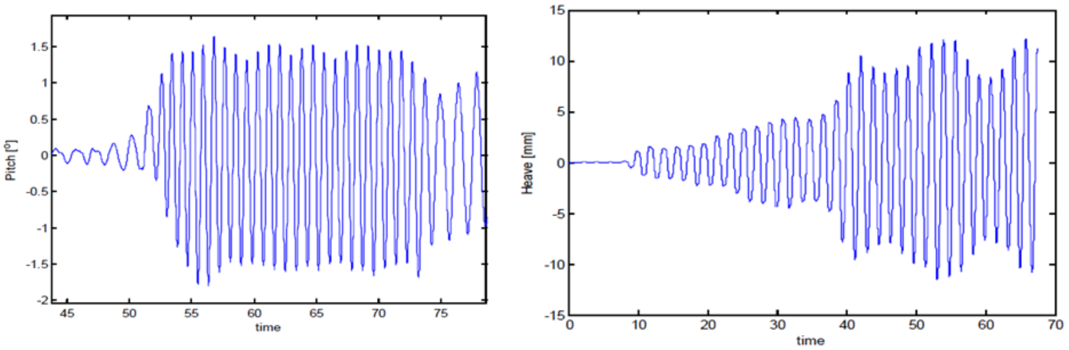

Figure 2.6. *Sample pitch and heave data for a test in matlab.*

For each test run thirty-five (35) each of the crests and troughs were sampled and the Root Mean Square (RMS) value estimated. The RMS values for wave, heave and pitch displacements became wave, heave and pitch amplitudes respectively. Next the Response Amplitude Operators (RAO) for each test run was calculated using Equations 2.1-2.

$$\text{RAO (heave motion)} = \left(\frac{H_a}{W_a}\right)^2 \tag{2.1}$$

$$\text{RAO (pitch motion)} = \left(\frac{P_a \times W_L}{360 \times W_a}\right)^2 \tag{2.2}$$

where, H_a and P_a = Heave and pitch amplitudes respectively

W_a and W_L = Wave amplitude and wave length respectively

Afterwards, the wave and ship response spectra were calculated using the International Towing Tank Conference (ITTC) wave spectrum (as in equations 2.3-5). Hence the area under each response spectrum known in wave statistics as the variance was calculated for the range of frequencies tested.

$$S_w = \frac{A}{\omega^5}\exp[-B/\omega^4]; A = 8.10\times10^{-3} g^2; B = \frac{3.11}{H^2_{1/3}} \tag{2.3}$$

$$S_H = \text{RAO (Heave motion)} \times S_w \tag{2.4}$$

$$S_P = \text{RAO (Pitch motion)} \times S_w \tag{2.5}$$

where, A and B = Constants

ω = Wave encounter frequency in rad/s

g = Acceleration due to gravity in m/s^2

$H_{1/3}$ = Significant wave height in m

S_w = Wave spectrum in $m^2 s$

S_H and S_P = Heave and pitch response spectra respectively in $m^2 s$

Finally, statistical averages of the wave, heave and pitch motion heights, periods and frequencies were also determined with the help of Equations 2.6-38.

For moments of the spectrum:

$$m_o = \int S_w d\omega \tag{2.6}$$

$$m_o^H = \int S_H d\omega \tag{2.7}$$

$$m_o^P = \int S_P d\omega \tag{2.8}$$

$$m_2 = \int \omega^2 S_w d\omega \tag{2.9}$$

$$m_2^H = \int \omega^2 S_H d\omega \tag{2.10}$$

$$m_2^P = \int \omega^2 S_P d\omega \tag{2.11}$$

$$m_4 = \int \omega^4 S_w d\omega \tag{2.12}$$

$$m_4^H = \int \omega^4 S_H d\omega \tag{2.13}$$

$$m_4^P = \int \omega^4 S_P d\omega \tag{2.14}$$

where, m_o, m_o^H and m_o^P = Wave, heave and pitch variances respectively in m2

m_2, m_2^H and m_2^P = Wave, heave and pitch second moments respectively in m2s-2

m_4, m_4^H and m_4^P = Wave, heave and pitch fourth moments respectively in m2s-4

For statistical averages of the wave and ship motion amplitudes:

$$\text{Most probable wave amplitude in m} = \sqrt{m_o} \tag{2.15}$$

$$\text{Most probable heave amplitude in m} = \sqrt{m_o^H} \tag{2.16}$$

$$\text{Most probable pitch amplitude in m} = \sqrt{m_o^P} \tag{2.17}$$

$$\text{Average wave amplitude in m} = 1.25\sqrt{m_o} \qquad (2.18)$$

$$\text{Average heave motion amplitude in m} = 1.25\sqrt{m_o^H} \qquad (2.19)$$

$$\text{Average pitch motion amplitude in m} = 1.25\sqrt{m_o^P} \qquad (2.20)$$

For statistical averages of the wave and ship motion heights:

$$\text{Average wave height in m} = 2.51\sqrt{m_o} \qquad (2.21)$$

$$\text{Average heave motion in m} = 2.51\sqrt{m_o^H} \qquad (2.22)$$

$$\text{Average pitch motion in m} = 2.51\sqrt{m_o^P} \qquad (2.23)$$

$$\text{Average of highest 1/10th waves in m} = 5.09\sqrt{m_o} \qquad (2.24)$$

$$\text{Average of highest 1/10th heaves in m} = 5.09\sqrt{m_o^H} \qquad (2.25)$$

$$\text{Average of highest 1/10th pitches in m} = 5.09\sqrt{m_o^P} \qquad (2.26)$$

$$\text{Average of highest 1/100th waves in m} = 6.67\sqrt{m_o} \qquad (2.27)$$

$$\text{Average of highest 1/100th heaves in m} = 6.67\sqrt{m_o^H} \qquad (2.28)$$

$$\text{Average of highest 1/100th pitches in m} = 6.67\sqrt{m_o^P} \qquad (2.29)$$

For statistical averages of the wave and ship motion periods:

$$\text{Peak period of wave motion in s} = 2\pi\sqrt{\frac{m_2}{m_4}} \qquad (2.30)$$

$$\text{Peak period of heave motion in s} = 2\pi\sqrt{\frac{m_2^H}{m_4^H}} \qquad (2.31)$$

$$\text{Peak period of pitch motion in s} = 2\pi\sqrt{\frac{m_2^P}{m_4^P}} \qquad (2.32)$$

$$\text{Mean zero crossing period of wave motion in s} = 2\pi\sqrt{\frac{m_o}{m_2}} \qquad (2.33)$$

$$\text{Mean zero crossing period of heave motion in s} = 2\pi\sqrt{\frac{m_o^H}{m_2^H}} \qquad (2.34)$$

$$\text{Mean zero crossing period of pitch motion in s} = 2\pi\sqrt{\frac{m_o^P}{m_2^P}} \qquad (2.35)$$

For statistical averages of the wave and ship motion frequencies:

$$\text{Average frequency of all upcrossing past a zero level for wave motion in rad/s} = \frac{1}{2\pi}\sqrt{\frac{m_2}{m_o}} \qquad (2.36)$$

$$\text{Average frequency of all upcrossing past a zero level for heave motion in rad/s} = \frac{1}{2\pi}\sqrt{\frac{m_2^H}{m_o^H}} \qquad (2.37)$$

$$\text{Average frequency of all upcrossing past a zero level for pitch motion in rad/s} = \frac{1}{2\pi}\sqrt{\frac{m_2^P}{m_o^P}} \qquad (2.38)$$

2.5. Description of How Data Was Organized

The processed data were separated into zero speed and forward speed each for heave and pitch motions. Afterwards, in each sub-grouping, intact ship data were separated from those of damaged ship (DS). Furthermore, damaged ship data were grouped into DS 100% CP, DS 80% CP and DS 70% CP. Therefore in each sub-group, there exist data for intact ship and damaged ship at 100% CP, 80% CP and 70% CP conditions.

2.6. Explanation of Appropriateness of the Methods and Procedures Used

Though numerical computations (using CFD) could have been used for the study, physical experimentation was chosen because it mimics the reality closely. Also as a preliminary study, physical experimentation will yield the factors which needs to be considered in numerical computations so that mathematical models can be developed. The third segment of the model was chosen for the damage because it was in the middle and would allow for symmetric flooding. In choosing the damage size, the focus was on a size which would not reduce the strength of the model. To mimic the flexibility of the ship hull, the rubber membrane was used to seal the gaps in-between model segments. This prevented water from sipping into the model whilst allowing the model to be flexible. Compartment permeability values chosen were based on ITTC recommended procedures for damage stability experiments as shown in Table 2.3.

Table 2.3. *Percentage values for CP recommended by ITTC.*

Compartment Type	Compartment Permeability (%)
Void space	100
Passenger or accommodation spaces	80
Engine room	70
Machinery room	70

Furthermore, the twenty (20) minutes in-between tests ensured that the tank water surface was calm before the commencement of a new test, otherwise waves of previous tests may interfere with those of current tests and influence the data acquired. Last but not the least, the form of grouping used in organizing the processed data, ensured comparison of results between intact and damaged ships, and for the damaged ship, between one value of CP and another, using the wave statistical parameters.

3. Results/Findings

3.1. Heave Motion Results

The moments of the spectrum and statistical averages of amplitudes, heights, periods and frequencies for the heave motion of the model at intact and damaged (100% CP, 80% CP and 70% CP) conditions were considered with the model moored stationary and at forward speed (1.4 m/s) too. The results are shown in Figures 3.1-9. The results shows variations in heave motion both at zero and forward speeds, when compartment permeability values were varied.

3.1.1. Variances of the Heave Motion

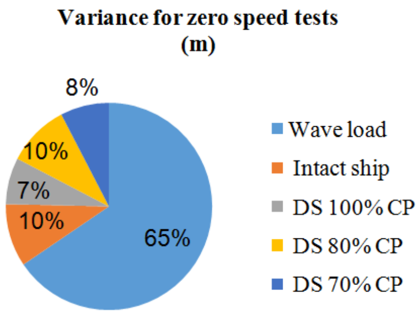

Figure 3.1. *Heave motion with model stationary.*

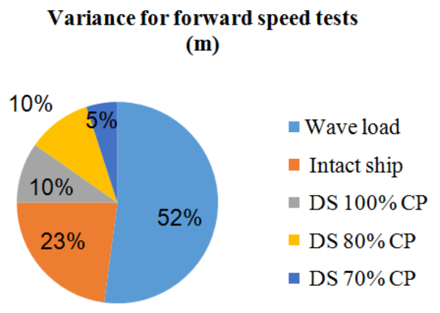

Figure 3.2. *Heave motion with model moving at 1.4 m/s.*

3.1.2. Statistical Averages of Heave Motion Amplitudes

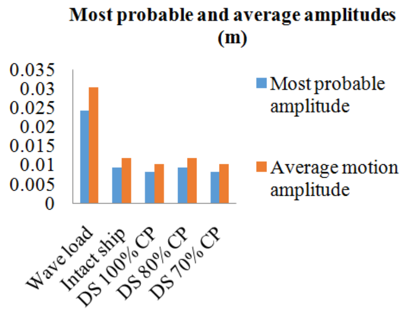

Figure 3.3*. Heave motion with model stationary.*

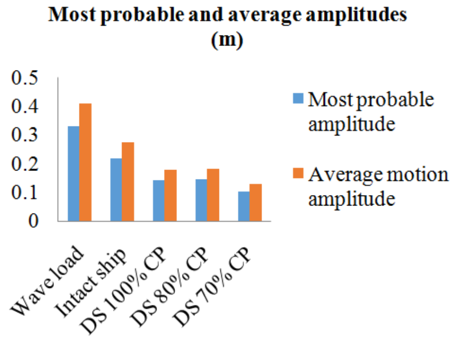

Figure 3.4. *Heave motion with model moving at 1.4m/s.*

3.1.3. Statistical Averages of Heave Motion Heights

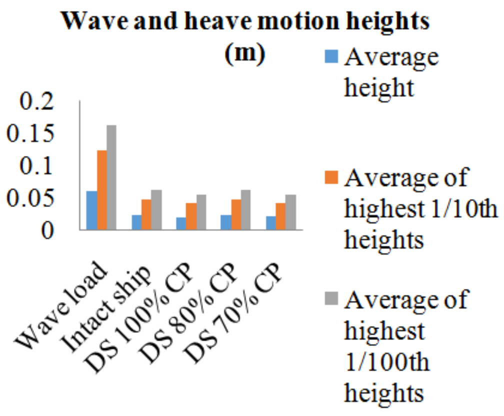

Figure 3.5. *Heave motion with model stationary.*

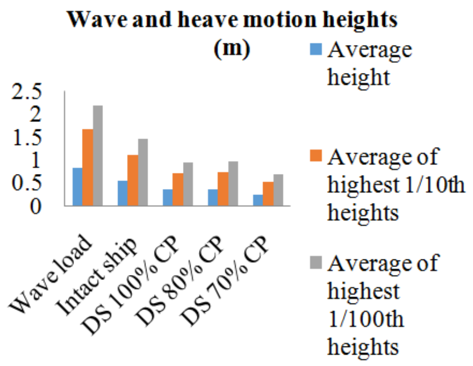

Figure 3.6. *Heave motion with model in motion.*

3.1.4. Statistical Averages of Heave Motion Periods

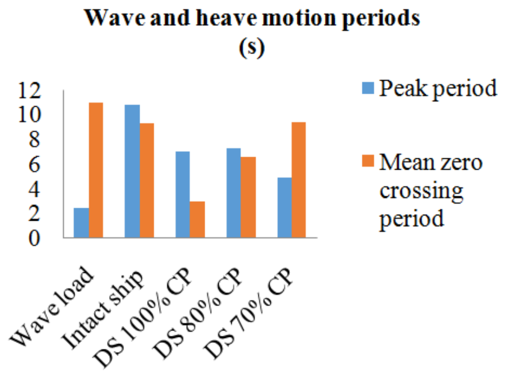

Figure 3.7. *Heave motion with model stationary.*

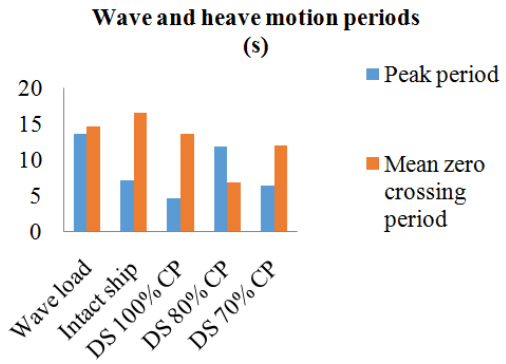

Figure 3.8. *Heave motion with model moving at 1.4 m/s.*

3.1.5. Statistical Averages of Heave Motion Frequencies

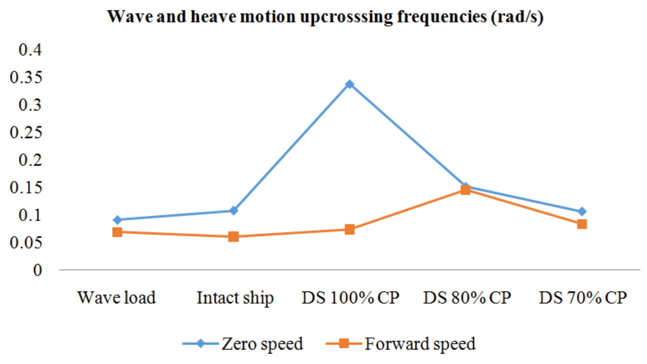

Figure 3.9. *Heave motion at zero and forward speeds.*

3.2. Pitch Motion Results

The moments of the spectrum and statistical averages of amplitudes, heights, periods and frequencies for the pitch motion of the model at intact and damaged (100% CP, 80% CP and 70% CP) conditions were considered with the model moored stationary and at forward speed (1.4 m/s) too. Figures 3.10-18 is showing the results. The results shows variations in pitch motion both at zero and forward speeds, when compartment permeability were varied.

3.2.1. Variances of the Pitch Motion

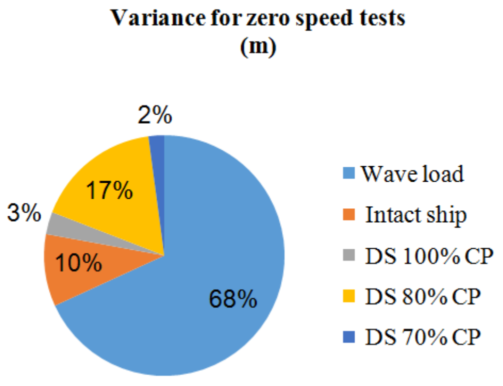

Figure 3.10. *Pitch motion with model stationary.*

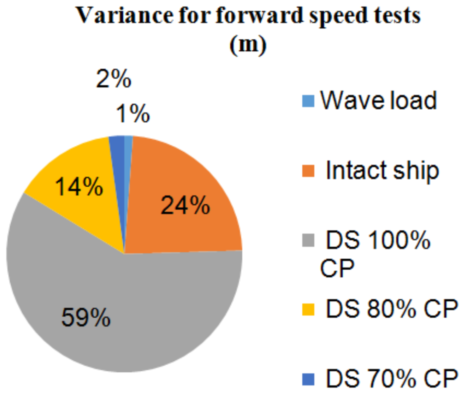

Figure 3.11. *Pitch motion with model moving at 1.4 m/s.*

3.2.2. Statistical Averages of the Pitch Motion Amplitudes

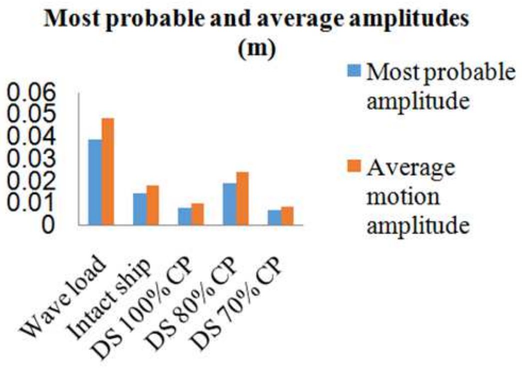

Figure 3.12. *Pitch motion with model stationary .*

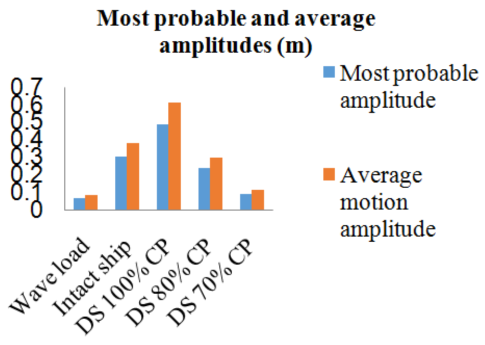

Figure 3.13. *Pitch motion with model moving at 1.4 m/s.*

3.2.3. Statistical Averages of the Pitch Motion Heights

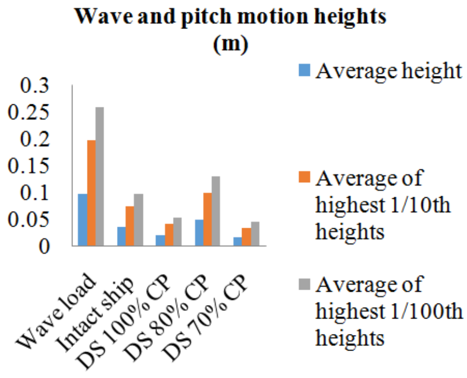

Figure 3.14. *Pitch motion with model stationary.*

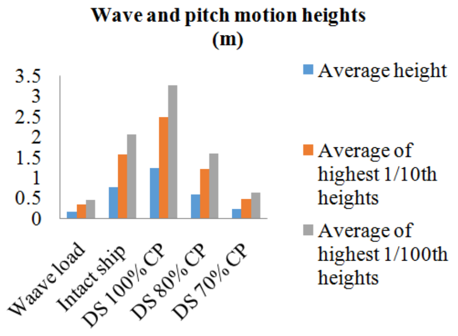

Figure 3.15. *Pitch motion with model moving at 1.4m/s.*

3.2.4. Statistical Averages of Pitch Motion Periods

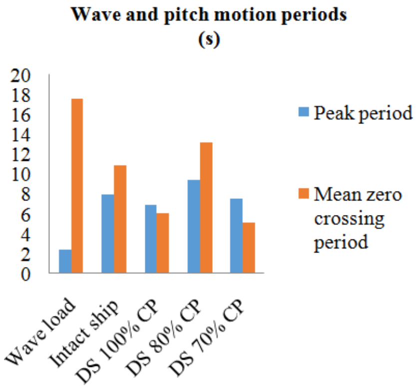

Figure 3.16. *Pitch motion with model stationary .*

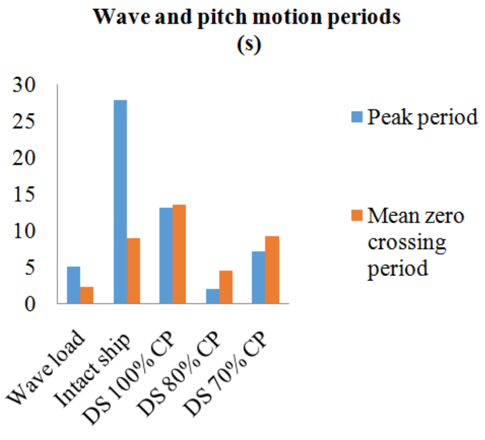

Figure 3.17. *Pitch motion with model moving with1.4m/s.*

3.2.5. Statistical Averages of Pitch Motion Frequencies

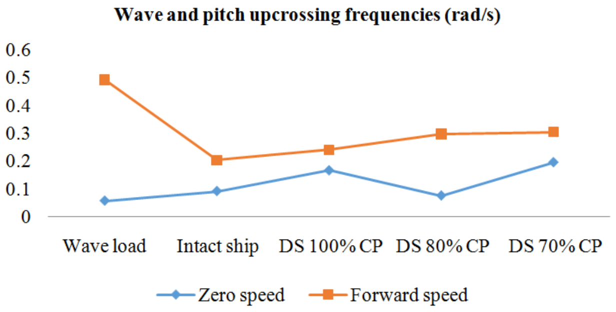

Figure 3.18. *Pitch motion with model stationary and in motion.*

4. Discussion and Conclusions

4.1. Discussion of Results for Heave Motion at Zero and Forward Speeds

The variance is the area under the wave and ship motion spectra. For the wave, it shows the magnitude of the wave load acting on the ship and in context of the ship, it shows the severity of the motions described by the ship in the given wave loading. The model experiences the highest motion when variance for the model is highest. Meaning if failure of the model would occur, then it is likely to happen when the variance is highest. Similarly, when variance is low then the loading on the model is less and it is unlikely to fail. In Figure 3.1, for the given wave load, the heave motion is severe when ship model is intact and also damaged with 80% CP. But the severity of the heave motion reduces when the ship model is damaged with 100% CP. However, in Figure 3.2, wave load confronting the ship model is reduced when compared with the wave load at zero speed. Heave motion is now severe when ship model is intact and less severe when damaged with 70% CP.

The motion amplitudes and heights describes how high the model has been displaced vertically up and down due to the wave loading acting on the model. Higher displacements means, the model is experiencing a greater impact of the wave loading and so likely to fail in this state. On the other hand, if the displacement reduces then the model is able to withstand the wave loading and is unlikely to fail. Hence from Figures 3.3-6 the highest most likely heave motion to occur is that for the intact ship model. If the model would fail, it is expected in this state whilst it is unlikely to happen when model is damaged with 70% CP.

The period also tells the interval of time within which the model is displaced and hence describes motions. When the period is small, the model would describe many motions (as compared to extended periods) within a given time and highly susceptible to failure. From Figures 3.7-8 using the mean zero crossing period, the model is highly susceptible to failure when damaged with100% CP and 80% CP at zero and forward speeds respectively, and less susceptible to failure when intact. However, considering the peak period, the model is highly susceptible to failure when damaged with 70% CP and 100% CP at zero and forward speeds respectively.

The frequency tells how often the model is displaced and hence describes motions. When the frequency is higher, then the model would heave (or pitch) more and highly susceptible to failure. From Figure 3.9 the area under the graph is greater at zero speed than at forward speed, with higher frequencies recorded for the damaged ship as compared to the intact ship. Therefore the model is highly susceptible to failure when damaged and stationary.

4.2. Discussion of Results for Pitch Motion at Zero and Forward Speeds

For the variance, from Figure 3.10, the pitch motion is severe when the model is damaged with 80% CP but reduces when model is damaged with 70% CP. However, from Figure 3.11pitch motion is now severe when model is damaged with 100% CP and less severe when damaged with 70% CP.

For the amplitudes and heights, from Figures 3.12-15 the highest most likely pitch motion to occur is that for the model damaged with 80% CP and 100% CP at zero and forward speeds respectively. If the model would fail, it will in these states whilst failure is unlikely to occur when model is damaged with 70% CP for both speeds.

For the periods, from Figures 3.16-17 using the mean zero crossing period, the model is highly susceptible to failure when damaged with 70% CP and 80% CP (same as heave motion) at zero and forward speeds respectively, and less susceptible to failure when damaged with 80% CP and 100% CP at zero and forward speeds respectively. However, considering the peak period, the model is highly susceptible to failure when damaged with 100% CP and 80% CP at zero and forward speeds respectively. This is the exact opposite of the results observed for heave motion.

And for the frequencies, from Figure 3.18 the area under the graph is greater at forward speed than at zero speed (the exact opposite of the results observed for heave motion), with higher frequencies recorded for the damaged ship as compared to the intact ship. Therefore the model is highly susceptible to failure when damaged and moving.

4.3. Current Results Compared with Previous

From the current study, results for 100% CP, 80% CP and 70% CP tests were different for the same speed (zero or forward) and motion (heave or pitch). But before the study, compartment permeability was only known to influence added mass and damping coefficients of a damaged ship section (Leblanc, 2011). Through the current study, it has been realized that compartment permeability has influence on heave and pitch motions of damaged ships. However the damaged ship motion response is not linear, meaning it cannot to be said that as compartment permeability reduces (from 100% to 70%) or increases (from 70% to 100%), heave and pitch motions also reduces or increases respectively. Therefore the damaged ship heave and pitch responses to varying compartment permeability values is non-linear, the motions may increase or decrease when compartment permeability values changes. This calls for further research in the subject area.

4.4. Summary of Conclusions

Extensive work was carried out to investigate the influence compartment permeability has on pitch and heave motions when ships are damaged. During the study a frigate ship model was used as the damaged ship and tested in Southampton Solent University towing tank facility when intact and also damaged with 100%, 80% and 70% compartment permeability values. In this study the major accent was on the use of wave statistical parameters in explaining the influence compartment permeability has on the heave and pitch motions of a damaged ship. The following observations were realized:

- Wave loads confronting a ship in a seaway are higher when the ship is stationary.
- The forward motion of ships influence the wave loads ships encounter and the corresponding ship motions.
- A damaged ship experiences less motions when the compartment permeability is reduced (to say 70%).
- Statistical spectral characteristics can generate additional information for data analysis.
- Compartment permeability influence heave and pitch motions of ships when damaged non-linearly.

4.5. Recommendations for Further Research

Based on the outcome of the study, future research works will focus on the following:

- Investigating the non-linearity in the influence of compartment permeability on damaged ship motions.
- Investigating the influence compartment permeability has on the structural response of damaged ships.
- Investigating how variations in the damage size may alter the influence compartment permeability has on damaged ship motions.

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References

[1] Anon. (2014). Worst cruise ship disasters in recent history. *http://www.wisn.com/money/travel/18534410*. Accessed: August 1, 2014.

[2] Bai, Y. (2003). *Marine structural design*. Elsevier Science Ltd: United Kingdom.

[3] Bishop, R. E. D. and Price, W. G. (1979). *Hydroelasticity of ships*. United States of America: Cambridge University Press.

[4] Chan, H. S., Incecik, A. and Atlas, M. (2001). Structural integrity of a damaged Ro-Ro vessel *Proceedings of the second international conference on collision and grounding of ships* (pp. 253-258). Technical University of Denmark, Lybgby.

[5] Korkut, E., Atlar, M. and Incecik (2003). An experimental study of motion behaviour with an intact and damaged Ro-Ro ship model. *DEXTREMEL Report.*

[6] Leblanc, P. L. (2011). *Hydrodynamic loading of a damaged ship section*. MSc. Thesis, University College of London, United Kingdom.

[7] Phelps, B. P. (1995). *Ship structural analysis: spectra and statistics*. DSTO Aeronautical and Maritime Research Laboratory. Australia.

[8] Smith, T. W. P. (2009). *Wave loading on damaged ship*. PhD Thesis, University College London, United Kingdom.

[9] Wood, C. D., Hudson, D. A. and Tan, M. (2009). CFD simulation of orifice flow for the flooding of damaged ships. *Proceedings of the 12th Numerical Towing Tank Symposium*. Cortona.

[10] Smith, T. W. P., Drake, K. R. and Wrobel, P (2009). Experiments on a damaged ship section. In C. Guedes Soares, and P. K. Das (Eds), *Second International Conference on Marine Structures* (pp. 27.16-18.3). Lisbon.