Seakeeping Behaviour of a Damaged Warship

T Andrewartha[1], G Thomas[2] and S Cannon[1]
[1]Maritime Platforms Division, Defence Science and Technology Organisation, Melbourne, Victoria, Australia
tristan.andrewartha@dsto.defence.gov.au
[2]Australian Maritime College, Launceston, Tasmania, Australia
g.thomas@amc.edu.au

ABSTRACT

In the unfortunate event that a naval vessel is damaged, decisions must be made regarding the reduction in the vessel's capability and what damage control procedures can be initiated to both restore this capability and minimise further damage. In order to make an informed decision, it is vital that Commanding Officers (COs) have access to reliable information regarding the vessel's structural integrity, stability and seakeeping performance. A reduction in any of these parameters may have a significant influence on the operability of the vessel.

A preliminary program of work has been conducted to investigate the change in ship motions due to an angle of list induced on the vessel after sustaining damage. This study incorporates both experimental and numerical simulations of a listed vessel at rest in a seaway. During the experimental program several parameters were investigated to ascertain their influence on the vessel's motions. These parameters include initial list angle, direction of list and wave conditions.

The results from this study show that for a vessel in beam seas there is no significant effect on vessel motions due to an angle of list. However, in head seas the introduction of an angle of list has a marked effect on the amplitude of roll motions. The example operator guidance generated shows that numerical modelling can be applied to the analysis of the operability of a vessel against set limiting criteria. This information and methodology could be incorporated into a rapid damage assessment tool along with sea-load predictions to assist COs in their decision making process in the event of an emergency.

INTRODUCTION

Recent incidents have occurred where a warship has sustained damage following an unexpected event. Whether the damage was sustained by offensive actions, such as that inflicted upon the USS Cole, or via accidents, such as the grounding of HMS Nottingham, the crew need to respond quickly to manage the situation. Within the commercial sector, organisations such as Lloyds Register of Shipping offer a Ship Emergency Response Service (SERS) that provides advice in situations similar to these. The objective is to save the ship and prevent loss of cargo or pollution of the sea. In the case of a warship, tools are being developed to provide onboard assistance to the crew following an incident. DSTO is currently developing a Rapid Assessment Tool for demonstrating the potential of these tools within the Royal Australian Navy (RAN). This paper reports on work which contributes towards the development of this tool, and in particular investigates the seakeeping behaviour of a ship which has an angle of list following damage.

DAMAGE SCENARIO

The terms Float-Move-Fight are often used to describe the extent of damage sustained by a warship. Following a damage incident the CO must rapidly assess the vessel's situation with respect to these three terms. If the ship is unable to float the situation is one of safely evacuating the crew. If the ship is able to float the CO must determine whether the vessel is able to move within the seaway. Depending upon the mission and the extent of damage this decision will be whether to move the ship to a safe haven for repairs or to continue the mission. Alternatively, if the damage is minor and the damage control processes have secured the ship the CO must decide whether systems onboard are operational or not. A typical scenario might be that as a result of damage the ship has sustained a list and it is the influence of this list on the operability of systems that needs to be determined.

A numerical and experimental analysis has been performed to assess the seakeeping characteristics of a vessel that has an angle of list after a damage event. Using *FD-Waveload* [1], a frequency domain, three-dimensional panel method seakeeping code, a series of vessel conditions were examined. In addition, model tests were conducted to assess the applicability of the code for predicting motions when the vessel is in a damaged state. The application of the numerical simulations is demonstrated through the development of operator guidance for a sample onboard system.

PREDICTION OF DAMAGED SHIP MOTIONS

The motions of a vessel can be modelled using several methods depending on the resources available and the output required. The simplest method is frequency-domain linear strip theory. Increasing in complexity, 3-D panel method codes in the frequency-domain allow greater flexibility in the types of scenarios that can be modelled and have the capacity to model more complicated shapes including catamarans. Some codes such as *FD-Waveload* have the capacity to model the motions of asymmetrical bodies. More complicated and computationally demanding still are time-domain seakeeping codes which also generally have the capacity to model non-linear effects and time dependent characteristics.

The simulation of intact ship motions in waves is based on a numerical solution to the six simultaneous equations of motions [2] given in a generic form in eqn 1. In this equation, M_{jk} are the components of the generalised added mass matrix, A_{jk} are the added mass coefficients, B_{jk} are the damping coefficients, C_{jk} are the restoring coefficients and F_j are the exciting force (j = 1..3) and moment (j = 4..6). The accuracy of the simulation is dependent on the accuracy of the determination of the hydrodynamic forces and moments [3].

$$\sum_{k=1}^{6}\left[\left(M_{jk}+A_{jk}\right)\ddot{\eta}_k+B_{jk}\dot{\eta}_k+C_{jk}\eta_k\right]=F_j e^{i\omega t}\ \text{for}\ j=1..6 \qquad \text{eqn. 1}$$

Examining the damaged ship scenario, some studies have been conducted using time-domain codes to compute motions. These have been coupled to computational fluid dynamics (CFD) codes to model the ingress/egress of water and free surface effects in parallel with the motions [3,4,5]. By modelling such a condition, the number of variables requiring consideration greatly increases. Since the vessel is taking on water, trim, list and displacement are all changing and the traditional equations of motion for a floating body are no longer valid due to constantly changing boundary conditions. When using coupled time-domain motion and CFD codes, the equations of motion are solved for each time step using the computed external forces. Not only does this increase the complexity of the model, but it also significantly increases the computational power and time required.

In order to simplify this very complex problem, the current study assumes that damage control procedures have been affected, and a new equilibrium condition with constant angles of list and trim, and draft is established. By making this assumption, it is possible to predict the motions of this vessel using a frequency-domain 3-D panel method code. The primary advantage of this approach is that each scenario is significantly quicker to assess than a time-domain simulation, which lends itself to the generation of operational guidance.

NUMERICAL PREDICTIONS

By examining a vessel with an angle of list, a degree of asymmetry is introduced into the problem. A 3-D panel method is more capable than a traditional strip theory seakeeping code of modelling the asymmetrical submerged surface and therefore *FD-Waveload* was utilised for this study. *FD-Waveload* is a frequency-domain, panel method seakeeping code which is based on the zero-speed Green function with a forward speed correction. Full details of the methodology can be found in [1].

A series of conditions was analysed using *FD-Waveload* including a variety of headings and angles of list. A preliminary study was first conducted to ensure that the results were not dependent on the hull form definition. This included a number of mesh sensitivity studies in both upright and listed cases to ensure consistent results across different mesh densities. Once it was established that there were no significant differences, meshes were generated for several different vessel attitudes including upright, and listed to 15 and 20 degrees to starboard.

MODEL EXPERIMENTS

A series of experiments was undertaken to assess the accuracy of the numerical predictions. These were conducted in the Australian Maritime College's (AMC) model test basin which forms part of the Australian Maritime Hydrodynamics Research Centre (AMHRC). This collaborative research organisation was established in late 2002 as part of the Australian Commonwealth Government's Major National Research Facilities Program by the AMC, DSTO and the University of Tasmania. The model test basin is 35 m in length, 12 m wide with a water depth of up to 1.0 m. Waves are generated by a multi-element piston-type wave-maker.

The vessel used throughout this investigation was a typical frigate (Figure 1). The principal particulars of the model and equivalent full scale vessel are given in Table 1.

The tests were conducted for both beam and head sea conditions for a series of different angles of list (Table 2). Throughout this testing program, the model was restrained using a bridle system similar to that used in past experimental investigations [6] (Figure 1). This system used weighted cords attached at the bow and stern of the model, ensuring that it was free to heave, pitch and roll and allowed partial freedom in surge, sway and yaw. The model's ballast was configured so that it could be readily moved to generate the required angle of list while attempting to maintain a constant roll radius of gyration.

Table 1 Vessel Principal Particulars

		Model 1:70	Full Scale
LBP (m)		1.578	110.5
B (m)		0.198	13.9
T (m)		0.064	4.45
Δ		10.682 kg	3600 tonnes
LCG fwd midships (m)		-0.061	-4.27
KG (m)		0.064	5.81
R44 (%B)	0 deg list	37.85	
	15 deg list	37.74	
	20 deg list	38.07	

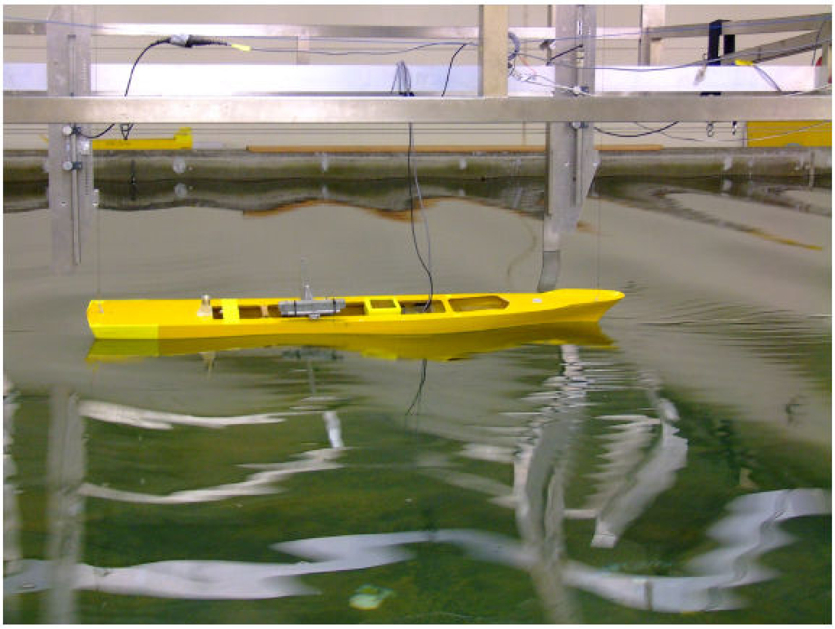

Figure 1 Frigate model restrained using bridle system

Table 2 Experimental Conditions

Condition Number	Vessel Heading (deg)	Initial Angle of List (deg)	Initial List Direction
1	90	0	-
2	90	15	Away from wave
3	90	15	Towards wave
4	180	15	-
5	180	20	-

Measurements were taken using a Crossbow NAV420 sensor, which is capable of measuring motions in six degrees of freedom, and a series of linear voltage displacement transducers (LVDTs). Roll decay tests were also conducted to determine both the natural roll period and the roll damping as a function of initial list angle. In this test the model was heeled over and then released. A time trace was taken of the rolling motions. This was then used to determine the roll damping coefficient and natural roll frequency.

RESULTS AND DISCUSSION

The results of the experiments were produced in the form of non-dimensionalised response amplitude operators (RAOs), allowing ready comparison between conditions. In order to correctly represent the listed vessels, the numerical mesh was offset such that the global origin occurred in the same *y*-plane as the listed centre of gravity. As a result, the rolling motions were modelled as relative angles both experimentally and numerically.

Figure 2a shows the roll motions of the frigate in beam seas for the two angles of list tested. Examining this RAO, there is little difference between the rolling motions of an upright vessel compared to a vessel listed to 15 degrees. This suggests that the rolling motions are not significantly affected by introducing an angle of list. Moreover, there is little discernable difference between listing the vessel towards or away from the waves.

D'Este and Contento [6] found that a listed vessel will exhibit different peak roll amplitudes to an upright vessel which is in contrast to the current investigations. This may be attributed to the variation in the submerged hull forms of the vessels. The previous study was based on a Ro-Ro, with a high block coefficient and well-defined bilge radius whereas the current study was based on a frigate hull form with a lower block coefficient (Figure 4). By listing the Ro-Ro, the underwater shape would be significantly altered, most likely affecting the roll damping, while the rounded form of the frigate would have less effect.

The heave results in beam seas (Figure 2b) show some degree of dependence on the angle of list. When the frigate was listed away from the wave, the heave motions between 0.3 and 1.2 rad/s were greater than for an upright vessel. When it was listed towards the wave, heave motions in lower frequency waves were found to be lower than for an upright vessel; however this trend is reversed for intermediate wave frequencies.

As expected, insignificant pitch motion was measured in beam seas (Figure 2c). The small pitch motion was due to the asymmetric fore and aft distribution of volume in the frigate hull form.

Considering Figure 3a, there was a clear relationship between angle of list and roll motion in head seas. This is most likely due to the submerged shape of the frigate. While an upright vessel is generally symmetrical about the centreline, the listed vessel is asymmetrical below the waterline. As a result, the forces acting on the hull are no longer symmetrical, resulting in a shift in the force balance which generates the rolling motion. Assuming that the upright vessel will not roll in head seas, comparing this with the 15 degree and 20 degree lists shows a distinct increase in rolling motions with increasing angle of list.

In head seas the experimental heave results (Figure 3b) show that increasing the list angle will for the most part not change the heave motions with the exception of a secondary peak which occurs at around 0.7 rad/s. This secondary peak increased with a larger angle of list. The angle of list had very little effect on the pitch motions in head seas (Figure 3c). This however is expected given that the longitudinal distribution of volume did not change greatly by listing the vessel.

When comparing the head seas and beam seas conditions it was found that the beam sea roll RAO is higher in magnitude for the list angles investigated. Therefore, the expected rolling motions would be less in the head seas condition. For example, with a list of 15 degrees, the roll RAO reaches double the magnitude in beam seas compared with head seas. This suggests that from an operational perspective it would be beneficial for a listed vessel to maintain a head seas condition, if possible, to minimise the rolling motions.

Examining the correlation between the numerical and experimental results, overall *FD-Waveload* predicted the motions of a listed vessel quite well. The roll RAO results in beam seas (Figure 2a) show a small increase in magnitude for an increase in angle of list, while little difference was visible between the 90 degree and 270 degree conditions. Comparing these with the experiments, the correlation was very good in terms of trends. There was however a slight shift in the resonant frequency, which affects comparisons for an individual frequency, particularly for those less than the resonant frequency. It is also interesting to note the difference in the peak area between the experimental and numerical results. The experimental roll RAO features a narrower peak region and will therefore have a smaller area under the curve. This will affect the results when sea spectra are applied.

In beam seas the comparison between the heave experimental and numerical results is less satisfactory than for roll and pitch. The trends derived from the experiments are however replicated to a degree in the numerical results (Figure 2b). For the condition with the frigate listed away from the waves, an intermediate peak is visible in the numerical results at approximately 0.7 rad/s. This appears to follow the peak in the experimental results. Similarly, a trough is evident in the experimental results in the listed toward the waves condition which is also replicated in the numerical results. While these trends are both identified in the numerical results, they are not as extreme as was visible in the experimental results. This will most likely also result in quite different motions with the application of sea spectra to determine the heave in irregular seas.

Little can be deduced from the experimental-numerical pitch comparison since they were of negligible magnitude (Figure 2c). However, a slight peak is clearly visible in both the numerical and experimental results.

Experimentally the roll magnitude increased with increasing angle of list (Figure 3a) in head seas. Similarly in the numerical results, a marked increase in roll magnitude was noted. As with the beam seas results, the resonant peak occurred at a lower frequency for the numerical results. In order to increase the clarity of the numerical trends, a series of extra list angles were modelled including 5, 10 and 25 degrees. These extra RAOs reinforce the theory that for an increase in list, an increase in roll magnitude can be expected in head seas. As with in beam seas, there is a clear difference between the area under the experimental and numerical head seas roll RAOs. This will be magnified when sea spectra are applied in order to extract the motions in irregular seas.

The numerical heave RAOs in head seas (Figure 3b) generally follow the experimental trends showing little difference between the two list angles. The main difference between these results is that the secondary peak is not visible in the numerical results. The numerical pitch results generally follow the trends visible in the experimental results but with very little difference in pitch motions between the different list angles (Figure 3c).

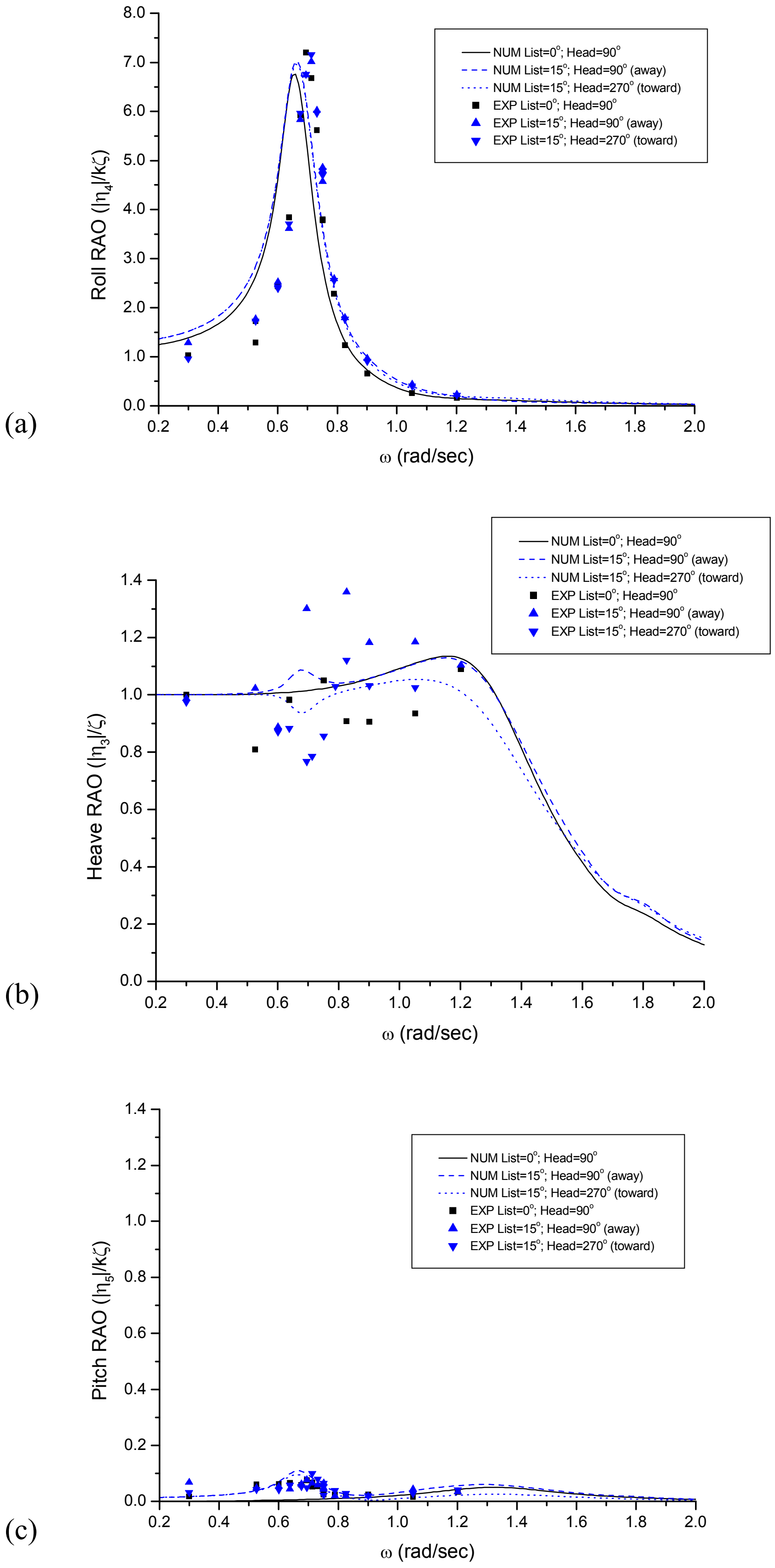

Figure 2 Beam seas RAOs; a: roll; b: heave; c: pitch

(a)

(b)

(c)

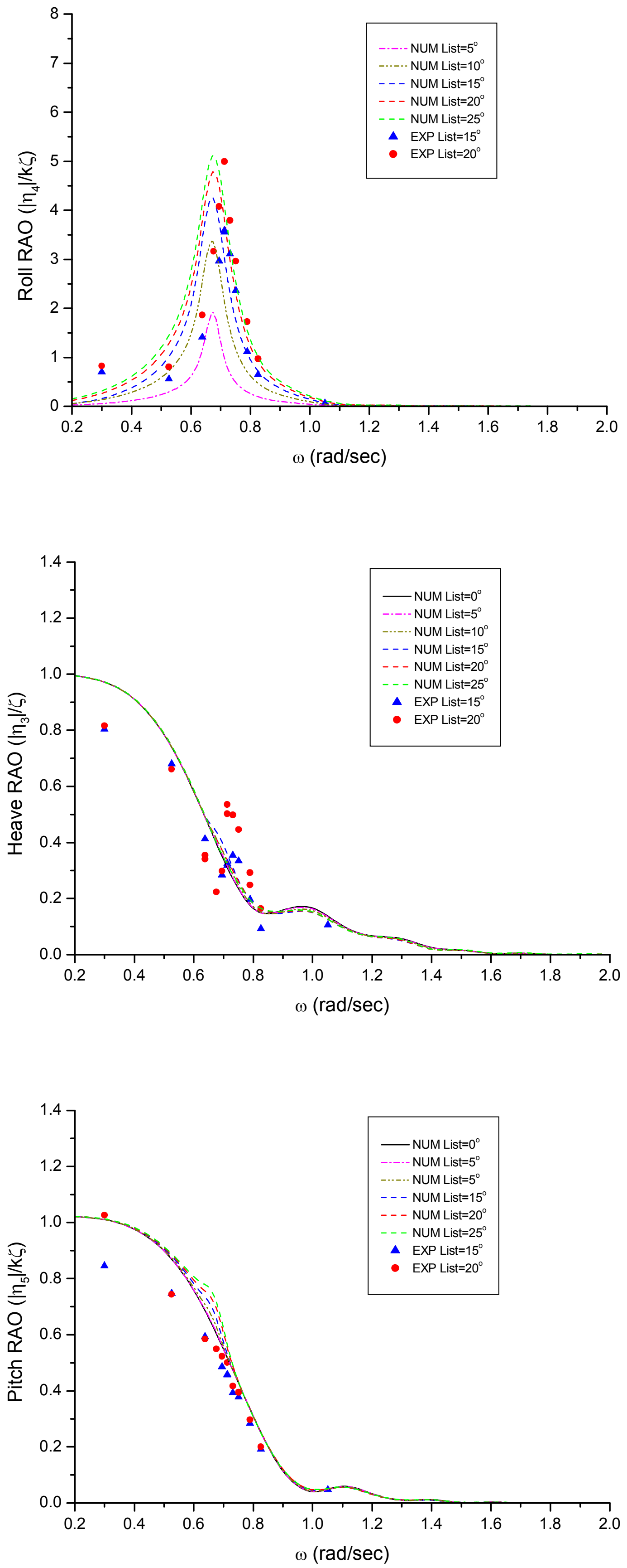

Figure 3 Head seas RAOs; a: roll; b: heave; c: pitch

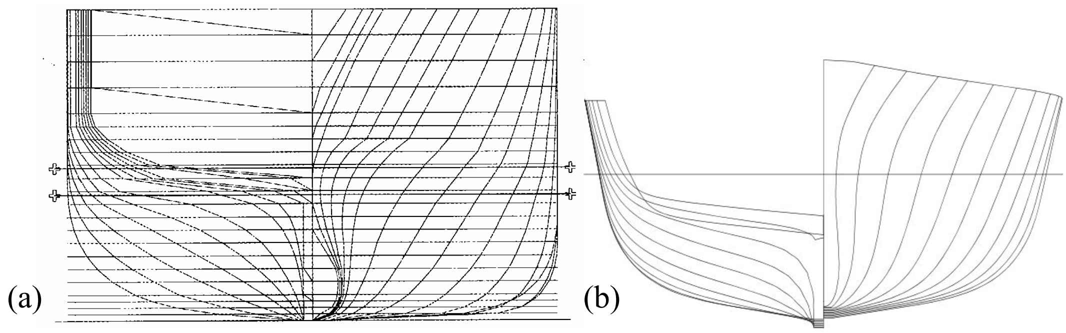

Figure 4 a: Ro-Ro body plan [6]; b: Frigate body plan

A roll decay test was also conducted on the frigate for the different angles of list. From the resulting time traces the natural roll period was found to remain constant at approximately 1.059 seconds model scale (8.37 seconds full scale). The roll damping coefficient however reduced with increasing angle of list (Figure 5). This may be attributed to the emergence of a bilge keel as the angle of list was increased and may explain the under prediction of roll motions in head seas for large angles of list.

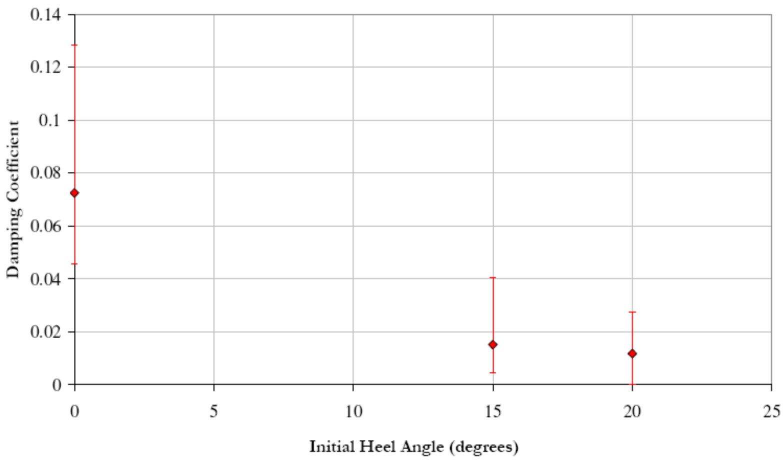

Figure 5 Calm water roll damping for different angles of list

The damping model used by *FD-Waveload* assumes that the vessel is symmetrical. Only the wetted surface area can be adjusted to take into account the angle of list, while the remaining parameters remain fixed for the different angles of list. As a result, only the relatively small frictional component of the damping is list angle dependent. By heeling the vessel over the damping characteristics may be altered, particularly in the instances where the bilge keels breach the free-surface. This occurred experimentally on a number of occasions particularly at large angles of list. In order to establish if this was the main contributing factor to the under-prediction, it would be necessary to modify the damping model to allow the asymmetry to be modelled; this capability is currently unavailable in *FD-Waveload*.

Overall, the results have shown that for the tested frigate hull form in beam seas, an angle of list will not significantly affect the roll motions. In head seas however, introducing an angle of list introduces an asymmetrical submerged form and will result in significant changes to rolling motions for the angles investigated. Generally, rolling will increase with angle of list. *FD-Waveload* is shown to give reasonable overall predictions of the motions of a listed vessel, both in head and beam seas. When considering individual frequencies however, there are some significant differences requiring further investigation.

EFFECT OF LIST ON SYSTEM CAPABILITY

A methodology for assessing the effect that the permanent list angle has on the operability of a particular ship system is demonstrated using the results obtained from *FD-Waveload*. By modelling the motions for a series of headings, speeds, sea states and angles of list, the performance of a damaged vessel can be compared to ship system limiting criteria. In this case study, the maximum significant roll amplitude that the sample on-board system can operate was used as a criterion. This limiting criterion was a roll angle of 17.6 degrees. In order to obtain the significant roll motion, the static list angle was added to the relative roll angle output from *FD-Waveload*. For example, for an angle of list of 15 degrees, the maximum allowable significant roll amplitude of the vessel would be only 2.6 degrees in the direction of the permanent list, whereas the maximum roll angle in the opposing direction could be 32.6 degrees from the equilibrium position.

Figure 6 shows two polar plots detailing the performance, against the limiting criteria, for different operating conditions (i.e. different angles of list). Figure 6a is for the upright condition, while Figure 6b is for a list of 10 degrees to starboard. Both plots are for operations in mean sea state 6, based on the ITTC two parameter sea spectrum. In these plots, the green region represents significant roll motions of up to 17.6 degrees and is allocated a pass rating accordingly. If the desired operating speed/heading combination falls in a red region, the significant roll motions could be expected to be greater than 17.6 degrees.

This is only a simplistic study and a full operability calculation could be performed as per the Materiel Requirement Set [7]. This would take into consideration the many factors contributing to the operability of a system, while the current study has merely considered the effect of an angle list on the capability of the system in terms of one limiting criterion in a given sea state.

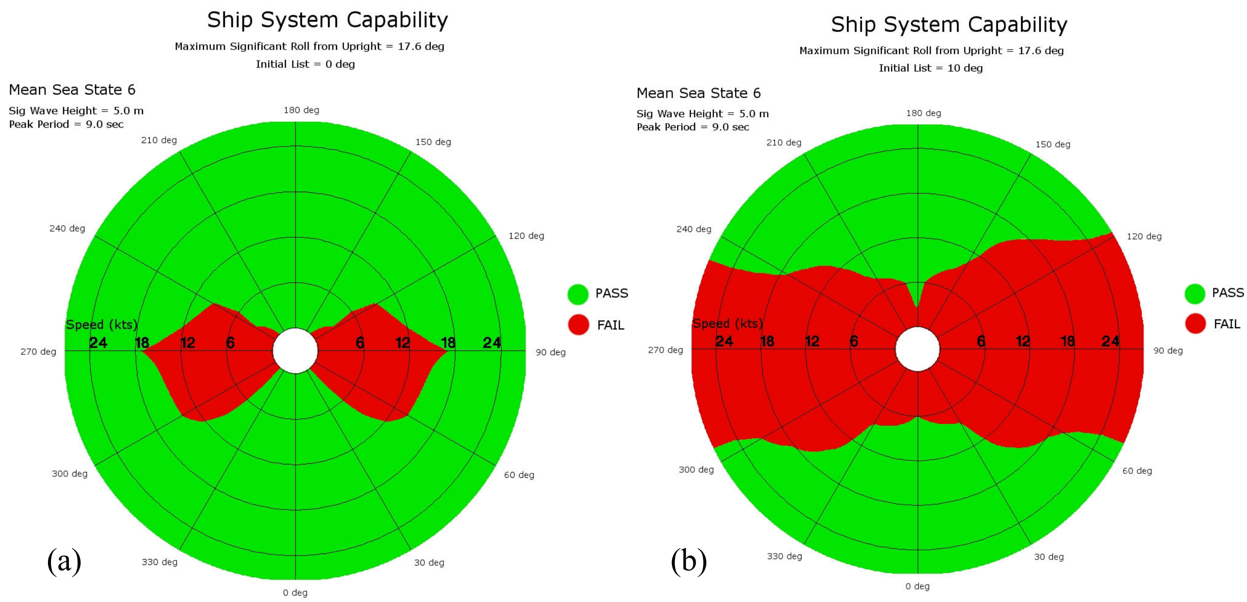

Figure 6 Frigate Ship System Capability - a: Initial List = 0 deg; b: Initial List = 10 deg

By comparing the red areas in Figure 6a and 6b, it is clear that by introducing an initial angle of list the system onboard the ship has a more limited range of operability. It is also important to note the asymmetry in this plot; with an initial list of 10 degrees to starboard, the motions are expected to be slightly larger with seas coming from the starboard side as indicated by the larger area of red.

Figure 7 shows the change in capability over a period of time for a damage event. The scenario discussed above forms part of the overall capability assessment. The capability of the ship system was determined by allocating a pass/fail rating to each point of the speed/heading matrix. By then comparing the total number of passes with the number of points in the matrix, the capability percentage was determined, in this particular case the operability of the ship system.

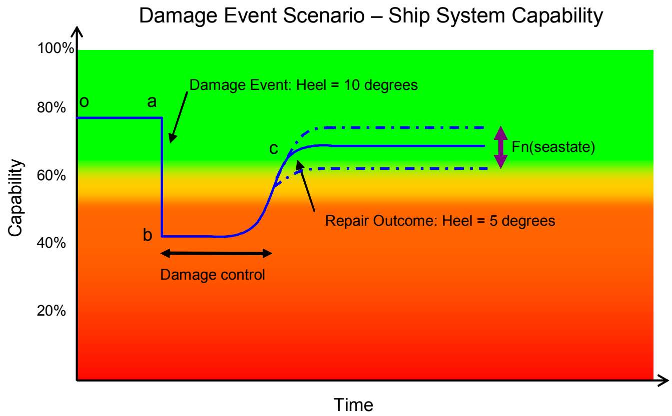

Figure 7 Effect of list on Ship System Capability

Considering Figure 7, based on the performance of an upright frigate in sea state 6, the system operability is 77 %. A damage event occurs at point *a* resulting in the vessel listing to 10 degrees (*b)*. In this condition the system capability drops to 42%. At this point, damage control procedures are put in place, such as cross flooding, which reduces the list to 5 degrees (*c*). The resulting operability level is dependent on sea state, but in sea state 6, this capability is now around 69%, a marked improvement from the operability whilst the vessel had a 10 degrees list. If it was not possible to correct the list, the reduction in system performance would place significant operational restrictions on the vessel.

This case study has only considered the effect of the angle of list on the performance of a particular system onboard a vessel. There are many other factors which should be considered including water ingress and the associated dynamic effects, as well as any damage to equipment and systems. A future aim is to generate an operator guidance tool to provide COs with more accurate data to make decisions on operational capability in a damage situation.

CONCLUSIONS

An experimental and numerical investigation has been conducted to examine the effect of an angle of list on the motions of a vessel. Experiments were first conducted to examine this effect, and provide valuable validation data for comparison with the results of the numerical code *FD-Waveload*. This work has led to the development of an example methodology for assessing the performance of a damaged vessel against set limiting criteria through the use of a case study.

The results of this study have shown that *FD-Waveload* has the capacity to predict the motions of a vessel with an angle of list with some limitations regarding prediction of responses at individual frequencies. Through the use of a case study, the results of this investigation have been applied to generate a concept for predicting the effect of list on the capability of an onboard ship system on a frigate. This methodology can be extended to examine any of a range of other limiting criteria applicable to naval surface platforms.

Along with the consideration of sinkage, free surface and sloshing, it may be prudent to extend this study to different types of hull-forms in support of the theory that the hull form body section affects the resulting motions with changing angle of list. Extending this study to take these factors into account will most probably result in the need for time-domain analysis to accurately model the fluid flooding in and out of the damaged compartment.

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