MODEL EXPERIMENTS AND SIMULATIONS OF A DAMAGED SHIP WITH AIR-FLOW TAKEN INTO ACCOUNT

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SUMMARY

To study the motion behaviour of a damaged frigate, tests have been performed in calm water and in waves of different heights and periods. The paper contains comparisons between experiments and simulations for selected conditions, that allow to highlight the effect of Air-Flow. Particular attention is also paid to transient flooding and roll transients, and to the effectiveness of cross flooding arrangements. Significant air flow has been observed during the experiments and the paper aims at assessing the importance of the phenomenon in modelling the behaviour of the vessel.

1 INTRODUCTION

In order to provide accurate simulations of the capsize of a damaged ship, efforts must be made for the modelling of the water behaviour inside the internal compartments. The water behaviour is influenced by a combination of the external pressure and velocities variation, ship motions and also behaviour of the air trapped inside the compartments. When the compartment is open and the air is free to escape (fully vented), no compression effect can occur. In this case the water simply behaves as a spring mass system. The mass being the mass of water inside the compartment and the spring being proportional to the water plane area inside the compartment. Such a spring mass system could yield to resonance when damping effects (friction, vortex and energy dissipation) are too small or neglected.

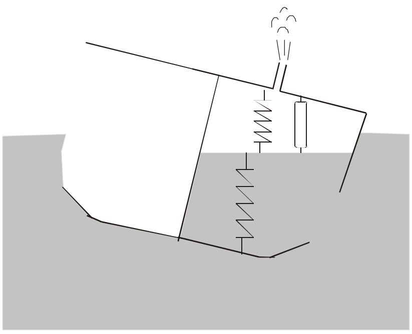

Figure1. Internal spring mass system

When the tank is closed, the air can not escape and acts as an additional spring. This spring is non-linear since it must obey the gas law: PV = constant. When a small volume variation is applied the relationship becomes PV=(P+dP)*(V+dV) which yields the spring formulation dP/dV= -1/V (P+dP). This type of behaviour can be simulated in the time domain but the above expression already shows that the spring is proportional to the inverse of the volume of air. Like for the case fully vented, we have here a spring mass system which can yield resonance when damping effects are neglected.

When air can escape, the relation PV = constant is still valid, but the volume to consider must account for the volume of air that escaped. In this situation, air compression can occur but the escape of air also results in energy dissipation. The modelling of the damage compartment resembles then strongly the principle of basic suspension. Hence, the air flow provides damping which limits resonance and can reduces significantly the motion behaviour inside the tank.

The obvious problem that is faced when air flow is not fully taken into account is that to reproduce the behaviour of water inside compartment equipped with vents, the simulation must be carried out with fully vented compartments in order that the static heel equilibrium is reproduce correctly. However, in this case no air compression can occur.

To obtain insight in the importance of the air flow on the global damaged ship behaviour, time domain simulations were compared with model tests. During these tests the ship was equipped with small vents, which allow the air to escape and were small enough to allow air to be compressed as well. To emphasise the effect of the flow modelling, calculations were repeated without air compression (fully vented) and with air compression but no air flow possibilities.

2 MODEL EXPERIMENTS

The model tests were performed in the facilities of QINETIQ, Haslar, on behalf of the Cooperative Research Navies (CRNAV) Dynamoc Stability group to provide a comprehensive set of validation data.. The model represents a Leander Frigate. The ship model was around 5 m long corresponding to a scale of 22. The model was fitted with appendages: rudders bilge keels and stabilizers. The ship was tested in two intact loading conditions which are summarized below:

	Condition 1	Condition 2
Displacement (t)	3029.0	3029.0
Draft (t)	4.36	4.36
GM (m)	0.36	0.77
Roll period (s)	16.0	10 s

Figure 2. Frigate model.

Four internal floodable compartments were modelled just aft of LCB. From aft to fore we find: 2 small wing tanks connected with a cross duct, a compartment extending form the center line to the starboard shell and a forward symmetrical compartment which extends across the full width of the ship. The forward and starboard compartments extend from keel level to the main deck, while the wing tanks are limited in height. This limitation causes the starboard wing tank to press full in each test. All compartments are separated with watertight bulkheads. The total compartment volumes are given below

	Volume
ST WING	86 m^3
PS WING	86 m^3
ST CENTER	324 m^3
SYM FWD	650 m^3

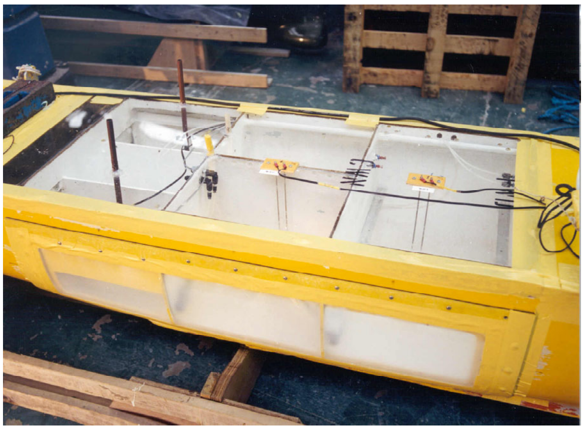

Figure 3. Frigate generic interior.

A damage opening was created instantaneously on the starboard shell. It extends along almost the entire length of the tanks. Vertically the opening extends from 2.8m above keel to 5.5m above keel. During the damage occurence becomes momentarily submerged. The wing tanks are connected by a cross duct. The cross duct is equipped with a valve, which allows one to close the cross duct. The same model was used in a study reported in ref. [1].

All compartments are equipped with vents of 10mm diameter. On the forward and starboard tanks they are placed as much forward and portside as possible in order to avoid air to be trapped. On the wing tanks, the vents consist of two vertical tubes, which start at the top of the tanks and extend above the main deck. These tubes are longitudinally placed in the middle of the tank and transversally as much portside as possible. The vent on the starboard side is located almost in the middle of the compartment.

The model tests were performed for several loading conditions and environmental conditions. This includes calm water damage, damage decays, damage decay sealed, decays without free surface (water replaced by corresponding steel weight), and damage tests in waves, regular and irregular. The paper compares the results of numerical simulations for a selected set of conditions.

Measurements concerned roll and heave motion, acceleration at COG, relative motion inside the compartments and video recording. A camera was also installed inside the ship to record the water behaviour in the wing tanks.

3 NUMERICAL MODEL

The theory for predicting large amplitude ship motions with the program FREDYN has been described in [2] and [3]. The derivation of the equations of motions for a ship subjected to flooding through one or more damage openings is based on the conservation of linear and angular momentum for six coupled degrees of freedom. Here the fluid inside the ship is considered as a free particle with concentrated mass; using this approach classical rigid body dynamics can be used to derive the equations of motion.

The static and dynamic wave pressure is calculated in the time domain over the instantaneous wetted surface. This accounts for a large part of the nonlinearities that affect the ship response. The added mass and damping are pre-processed in the frequency domain using a strip theory module. They are transformed into convolution integrals (retardation function) to be included into the equation of motion which is treated in the time domain. Wind forces, empirical manoeuvring drag forces and damage forces are included as well in the equation of motion. During damage simulations the time varying mass and inertia are also accounted when solving the equation of motion.

Water ingress and fluid loading

To estimate the flow rates of water entering a compartment, the flooding model is based on the Bernoulli equation, see [3]. This analysis is applied to each damage opening or holes between two compartments. It assumes stationary flow conditions at each time step and no loss of energy due to friction or increased turbulence. Based on the difference in pressure head, the velocity through a damage opening can be calculated. In addition, air flow and compression effects are modelled using the appropriate gas laws.

Figure 4 presents a sketch for the flow through an orifice, where the discharge velocity is given by:

$$v_2 = \sqrt{2g(H_1 - H_2)} \qquad \text{(m/s)} \qquad (1)$$

When air pressure can build up inside the compartment the velocity expression becomes:

$$v_2 := \sqrt{2 \cdot g \cdot (H1 - H2) + 2\frac{(P1 - P2)}{\rho}} \qquad \text{(m/s)} \qquad (2)$$

where P1 is the outside atmospheric air pressure and P2 the internal air pressure. ρ is the flood water density.

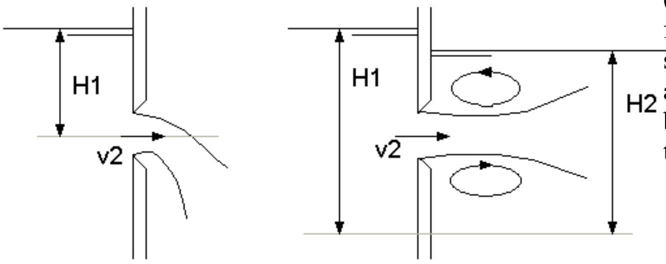

Figure 4. Flow through a free discharging orifice (left) and through a fully submerged orifice (right)

To obtain the total discharge through an opening, the following empirical formulation is used:

$$Q = C_d v_2 A \qquad (\text{m}^3/\text{s}) \qquad (3)$$

where A is the area of the opening and C_d is the discharge coefficient. This coefficient accounts for a combination of several effects (such as friction losses).

In case of an opening with the open atmosphere, the air flow velocity is calculated considering the air pressure P_c inside the compartment. The Bernoulli formula is applied which yields for the air velocity:

$$v_a := \sqrt{\frac{2(P_c - P_1)}{\rho_a}} \qquad \text{(m/s)} \qquad (4)$$

where ρ_a is the air density, P_c the air pressure inside the compartment and P_1 the atmospheric pressure..

Similarly, the volume rate is calculated with

$$Q := C_d \cdot v_a \cdot A \qquad (\text{m}^3/\text{s}) \qquad (5)$$

where A is the net area of the opening and C_d is a discharge coefficient. The simulations were realised with an air discharge coefficient equal to 1.0.

In case of multiple compartments the program handles the pressure and flow relationship between all compartments that can have complex layout with multiple openings.

Quasi-dynamic fluid loading

Based on the computed inflow and outflow of fluid through all openings, the fluid mass inside a compartment is known at each time step. A simple yet practical approach is to assume that the water level of the flood water inside any compartment remains horizontal (earth-fixed) at all times. This implies that the damage fluid causes a vertical force (due to gravity) to act on the ship and that any sloshing effects are neglected. The associated ship-fixed force and moment components can be determined through the appropriate transformations; these are then added to the equation of motion.

4 RESULTS OF SIMULATIONS AND COMPARISON WITH MODEL TEST

4.1 CALM WATER DAMAGE

During the experiments, the opening was closed with a latex sheet which was pierced at the start of the experiment to create an instantaneous damage. The damage occurs in less than 1/25s at model scale (less than 0.2s on real scale). In calm water, simulations have been performed using the different approaches:

- modelling of air compression and air flow through the vents (as in the model tests);
- modelling of air compression without air flow;
- fully vented compartments, the air pressure inside compartment remains to the atmospheric level.

Figures 5 through 8 show the comparison for the four different configurations GM = 0.36m and GM = 0.77m with cross duct ON (open) or cross duct OFF (closed).

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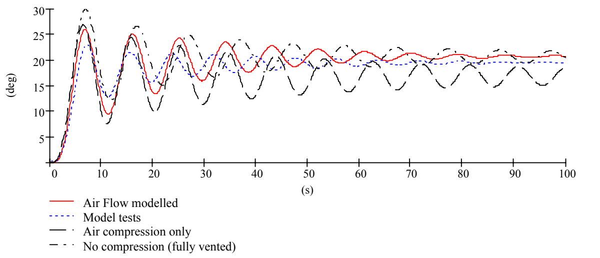


Figure 5. Calm water damage - GM = 0.77 m - Cross duct OFF.

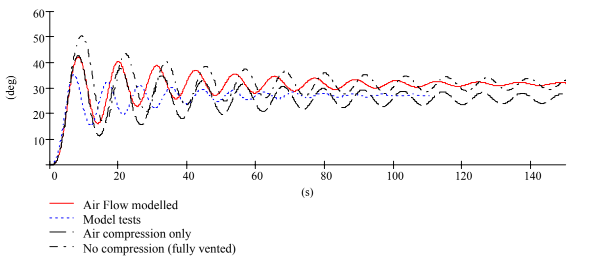


Figure 6. Calm water damage - GM = 0.36 m - Cross duct OFF.

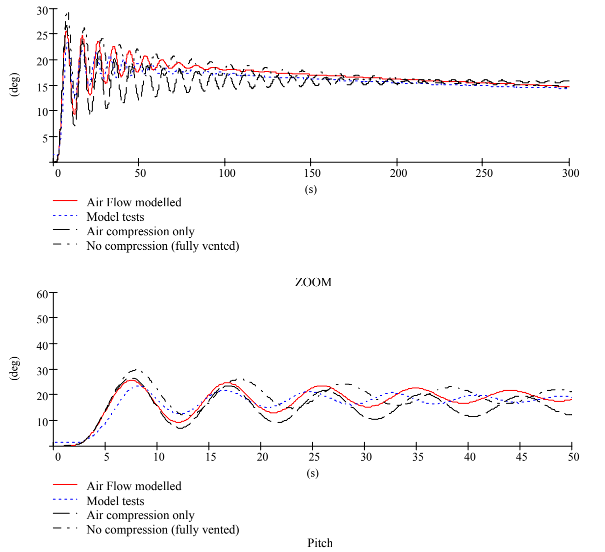


Figure 7. Calm water damage - GM = 0.77 m - Cross duct ON.

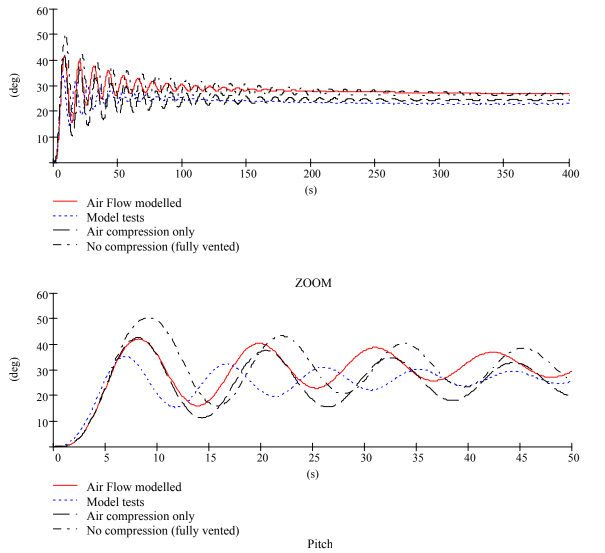


Figure 8. Calm water damage - GM = 0.36 m - Cross duct ON.

The static heel angle is reproduced well during the air flow simulations and the fully vented simulations in the cases of "high" GM = 0.77m. In the case of "low" GM = 0.36m, the static heel angle is overestimated by around 5 deg. This difference has not been fully explained yet, but might be attributed to the small slope of the damage restoring arm curve (see Figure 9), which should yield a most sensitive situation. Small variations in the damage moment yield large heel angle differences.

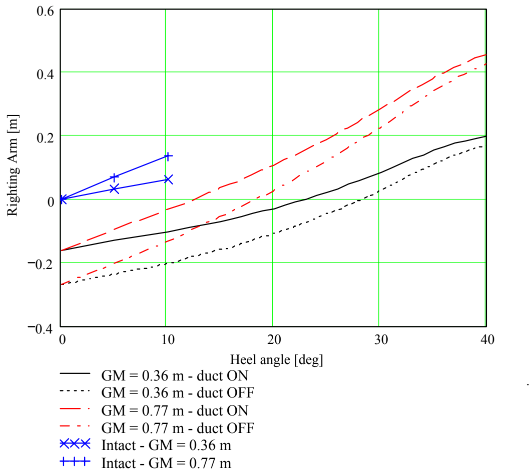


Figure 9: Free Flooding and Intact Hydrostatic - Righting Arm Curves

However, the calculation trends are found as expected: When air is trapped (air compression only), and the cross duct is OFF, the static heel angle is smaller since the water ingress inside the compartment is limited by the increase of air pressure. For both fully vented and air flow simulation the static heel angle is the same whatever the damage condition. Note that in the case of high GM with Cross duct ON (Figure 7), the static heel angle is larger in the case of air compression only. This is due to the fact that the pressure increase limits the amounts of water in the portside wing tank which limits the slow heel recovery offered by the cross duct opening. This slow heel recovery seems well reproduced for all cases.

Damping effect is clearly visible when air flow is modelled. The roll oscillation disappears rapidly as it can also be observed in the test results. When air flow is not modelled, the damping seems much smaller and oscillations take longer to disappear. This seems to be the illustration of the expected phenomenon. The water still oscillates strongly in the compartment when air flow is not modelled.

The damage roll period is not very well predicted, while the comparison with intact decay tests shows a very good agreement for both roll period and damping.

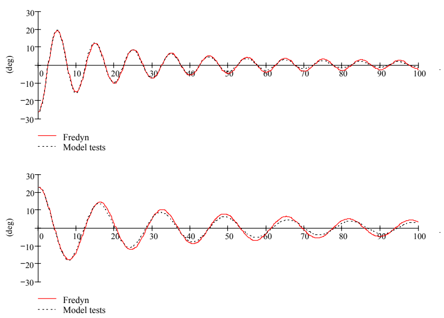


Figure 10: Intact roll Decay Tests - Top GM = 0.77 m - Bottom: GM = 0.36 m

Note that these results have been obtained direcly without any tuning of the roll damping. Fredyn uses an empirical visous damping formulation that has been specially derived for frigate ship type.

The change of roll period due to the water inside the compartment is not very accurate. It is expected that the assumption made on the inertia of the volume of water contained in the compartment is too crude. An improvement should be performed and being tested. The following values are observed for the roll natural periods:

Case	Calm Water Damage				Intact
	Model test	Simulation			
		Air Flow	Air Comp.	Fully vented	
GM=0.36m Duct OFF	9.1	11.4	11.9	11.8	16.4
GM=0.36m Duct ON	9.6	11.4	11.9	11.8	
GM=0.77m Duct OFF	8.1	9.0	9.3	10.0	10.0
GM=0.77m Duct ON	8.2	9.2	9.4	10.3	

It should be noticed that the damage roll natural periods are significantely smaller than the intact periods. This is explained by the slope of the free flooding righting arm curves. Around the equilibrium position the slopes are higher than those of the intact cases. Which means that when the ship is damaged, the roll stiffness increases. This is due to the small GM of the intact ship. The water inside the compartment significantly lower the center of gravity. This yields a larger effect on the GM than the inherent free surface effect. To obtain smaller roll natural period when the ship is damaged, the effect of the inertia increase should then be smaller than the effect of the stiffness increase.

The transient roll motion is described in section 4.3. The roll overshoot is overestimated in the calculations. The largest overestimation occurs when the compartments are fully vented. This is due to the fact that a larger amount of water can flood during the transient phase. The predictions with or without air flow are similar as soon as air compression is taken into account. It shows that air compression is an important factor for this phase of the damage and that the air flow has a minor influence.

4.2 REGULAR WAVES

Tests were performed in regular waves. Since air flow damping effect has been observed during the calm damage, this effect is also expected in waves. Resonant behaviour of the water inside the compartment might be avoided. The figures below illustrate the roll motion for a variety of regular waves.

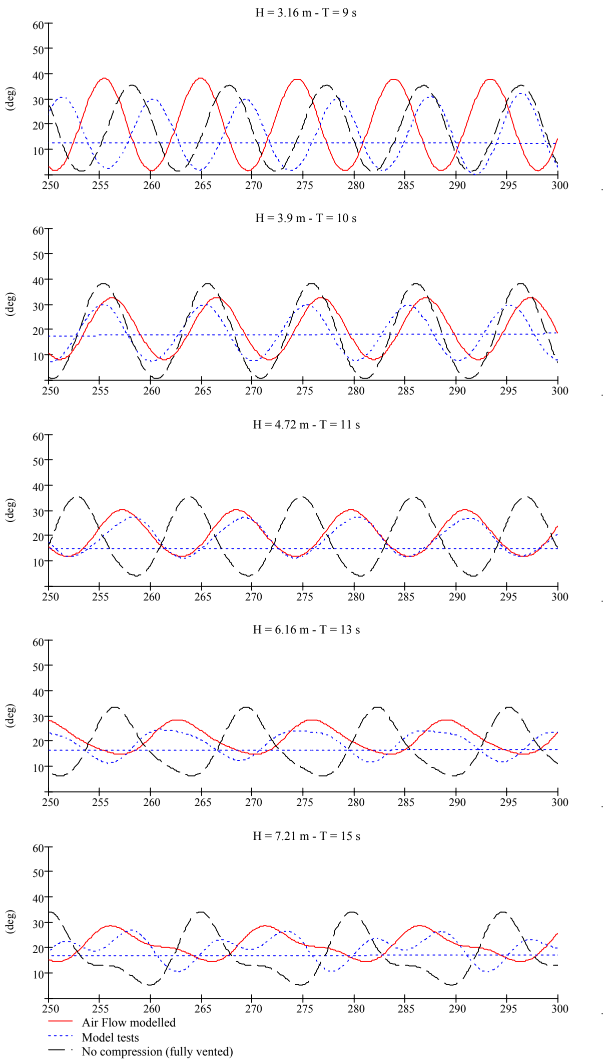


Figure 11. Roll Motion in Regular Waves - GM = 0.36 m - Cross duct OFF.

The agreement between the model tests and the calculations appear satisfactory and a clear improvement is observed when taking air flow into account. One might notice that in the 9s wave, the calculation overestimates the roll motion to starboard. However we must remind the error made in the natural period of the damage ship. The model test indicates 8.1 s while the calculation shows 9.0s. Being right on top of the natural period seems to be the reason to overestimate the motion. The behaviours obtained for the all the damage conditions are summarized in the 4 figures below:

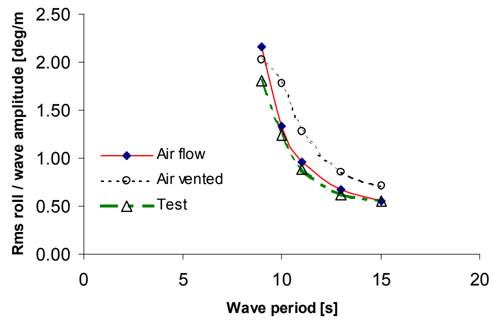


Figure 12. Damage Roll Response - GM = 0.77 m - Cross duct OFF

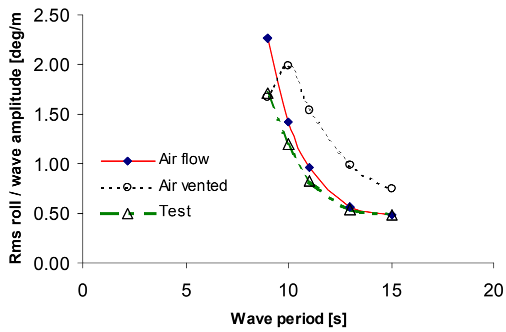


Figure 13. Damage Roll Response - GM = 0.77 m - Cross duct ON

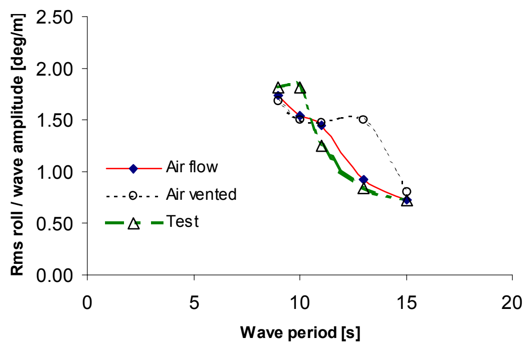


Figure 14. Damage Roll Response - GM = 0.36 m - Cross duct OFF

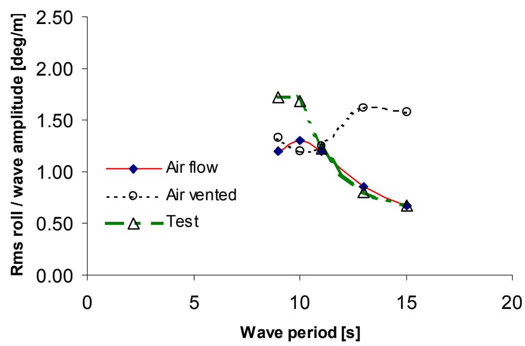


Figure 15. Damage Roll Response - GM = 0.36 m - cross duct ON

The figures show the rms of roll divided by the wave amplitude as a function of the wave period. They clearly show that the air flow simulations are always closer to the model test. In case of vented compartment large motion are observed especially in the long wave range. The figures also show that the peak of the response is not clearly present, as shorter wave periods should have been tested.

4.3 TRANSIENT BEHAVIOUR

A trend result in the simulation is the overestimation of the maximum heel angle reached just after the transient phase. The differences observed range from 3 deg, in case of "high" GM, to 8.5 deg with the "small" GM. This heel angle is reached 7.3 s after damage. To gain insight in the transient process the available measurements during the first 7 seconds have been analysed in the case of the high GM and cross duct OFF.

4.3.1 Inflow in the Starboard Wing Tank:

As can be seen in Figure 16, the water in the wing tank is responsible to a large extent for the calculated total heeling moment during the first 4 seconds. The figure corresponds to the high GM with cross ON

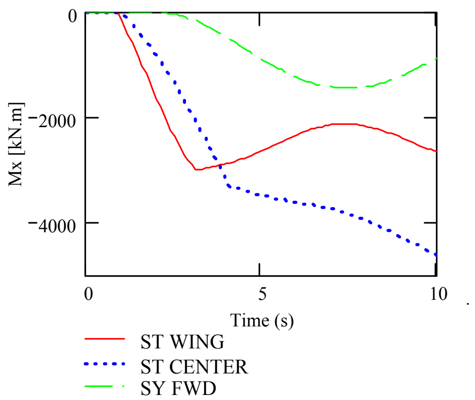
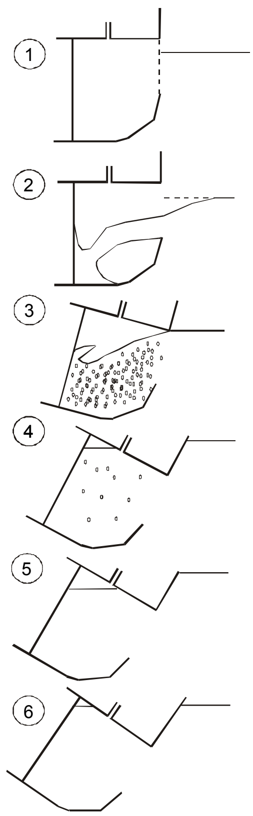


Figure 16. Calculated Heel Moment during initial stage of flooding.

The onboard camera allowed to analyse precisely the flooding sequence. It is summarised in Figure 17.



1. t = 0s, opening created

2. t = 0.8s, the jet touches the bottom of the tank with a delay. The external water level drops about 0.5 m at the edge of the opening.

3. t ~ 2.5s, the opening is submerged, air compression starts to play. Water inside compartment is about 50% internal volume and is saturated with air.

4. t = 5.1s, water level inside compartment reaches a first maximum, air is dynamically compressed

5. t = 6.4 s, water level drops, due to extra air compression.

6. t =7.1, water level reaches new maximum,

7. t = 7.3 maximum roll angle

Figure 17. Sequence of flooding water in starboard wing tank

A wave probe was fitted along the portside bulkhead of the starboard wing tank; the measured and computed signals are compared in Figure 17.

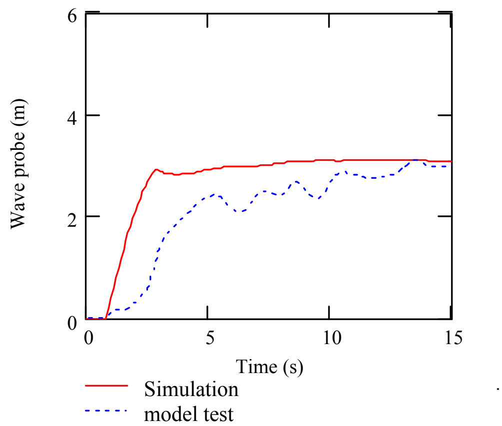


Figure 18. Measured and calculated water level in ST WING compartment.

In the simulation, the water level increases much faster initially indicating that the inflow is overestimated in the 3 first seconds. Note that during the calculations, there is no delay between the time of opening and the time that the water reaches the bottom of the tank. The above signals have been shifted accordingly. At t=2.5s, the calculation also shows a change of inflow which corresponds to the submergence of the opening. However, at that time the amount of water is at nearly 90% capacity of the ST WING compartment.

Possible causes of this difference are:
Small compartment compared with the size of the opening, air-water mixing, effect of the drop of water surface outside the damage opening, error due to the time step organisation (the flow is calculated at each time step and the amount of water corresponding to this flow during one time step (0.1s) enters the compartment), or flood water dynamic.

A reduction of the discharge coefficient would reduce the flow during the first seconds. With Cd = 0.3, we obtain a similar inflow during the 3 first seconds. However once the opening is submerged the inflow appears to be slightly underestimated.

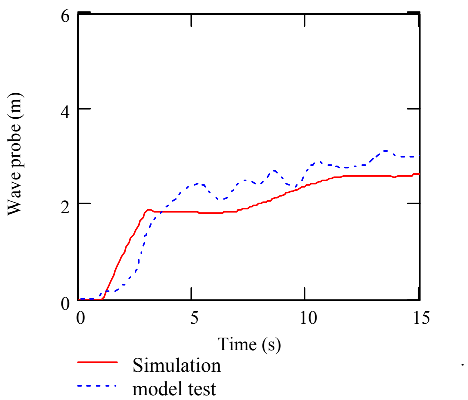


Figure 19 : Measured and calculated water level in ST WING compartment. Cd = 0.3

This reduction of discharge coefficient improves the calculated roll maximum, see Figure 19. The remaining difference is expected to be related to transient sloshing inside the forward symmetrical compartment.

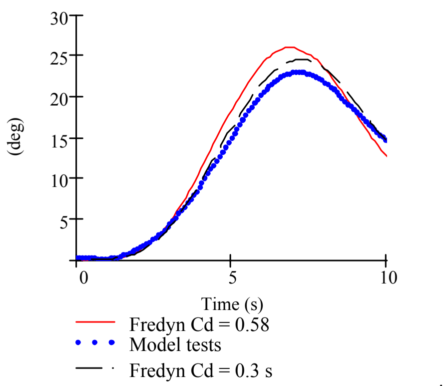


Figure20: Calculated and measured Roll motion during transient phase.

4.3.2 Inflow in the Portside Wing Tank

When the cross duct is opened the portside wing tank fills in slowly. The tank reaches is maximum level about 400s after damage. Figure 21 shows the agreement between model test and simulation. The main trend is reproduced but the filling-in is found slower in the calculations, especially in the begining. In the simulations the tank is full after 500s.

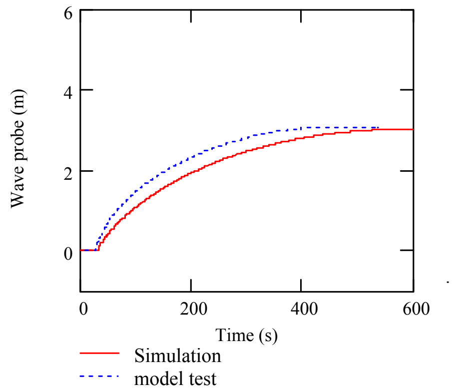


Figure 21: Measured and calculated water level in PS WING compartment.

4.3.3 Inflow in the Forward compartment:

No video recording was made of the water behaviour inside the forward compartment. The only measurement available comes from the wave probe, which is located in the center line of the ship. Figure 22, shows that the water level remains very small during the 5 first seconds. It is then followed by a sudden increase of the water level.

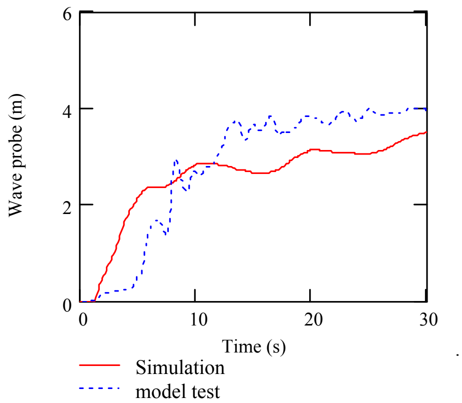


Figure 22: Measured and calculated water level in Symmetrical Forward compartment.

Since the inflow in this compartment is similar to the inflow of the other compartments, we assume that the time that it takes for the wave probe to measure the rapid increase of water level is related to the motion of a bore to the portside (also starboard) direction. This internal wave will reflect on the portside shell and then come back to the centre of the compartment, which creates the sudden increase 5s after damage. This assumption is illustrated in Figure 23. If this assumption is correct, it will yield a different heeling moment than the one computed. In the calculation the moment is negligible during the first seconds because the compartment is symmetrical and the ship has no heel.

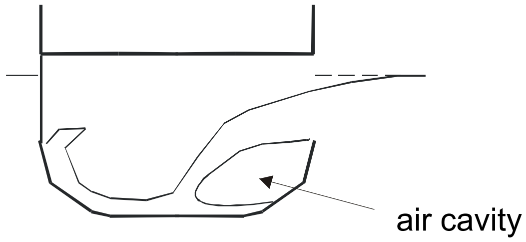


Figure 23: Expected water behaviour inside forward tank during the first seconds.

Since the water touches the bottom with an initial transverse velocity, it is expected that a large amount of water would flow to the portside and to the starboard side. In this case the heel moment created by the forward compartment would be different from the simulated result.

5 CONCLUSION

Model tests with a damage frigate where air flow was present have been reproduced by means of numerical simulations. The calculations showed a clear improvement when air flow through the vents is taken into account. Air flow effects may result in extra roll damping and computed roll motions in waves get closer to the test results. This has been observed for two loading conditions with and without cross duct. The paper analyses also the behaviour of the water during the transient phase which follow the damage. It is observed that calculations overestimate the transient maximum roll angle. This overestimation is expected to be related with an overestimation of the inflow inside the small wing tank and with a potential momentary sloshing inside the forward compartment.

Based on the above observation it seems justified to conclude that air flow must be taken into account for the simulation of a damage vessel.

6 AKNOWLEDGEMENT

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