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ON THE MODELLING OF FLOODWATER DYNAMICS AND ITS EFFECTS ON SHIP MOTION

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SUMMARY

Investigations of the flooded ship behaviour after damage require the development of sophisticated numerical models of good efficiency to enable their practical implementation. A brief outline of recent developments of the NTUA-SDL numerical method (code CAPSIM) and an experimental/numerical validation study of the employed floodwater dynamics model are presented. Finally, the basic limitations of the employed model are discussed.

1. INTRODUCTION

A most significant problem of Ro/Ro-passenger ferries safety is the potential accumulation of floodwater on the large, unobstructed car deck area, besides in other spaces, in case of damage. The gradual accumulation of water on deck strongly depends on a variety of dynamic phenomena, especially when the ship is moving in a seaway, strongly affects the motions of the vessel and vice versa the flooding mechanism, with the possible loss of stability or capsize when particular conditions are met.

Two phenomena may be identified to take place during the flooding procedure. These are the water ingress/egress mechanism and the internal motion of the accumulated water, including its interaction with the ship motion. Both phenomena are physically coupled, but this coupling can be mathematically approximated by different modelling techniques enabling fast numerical simulations of the ship's behaviour at acceptable level of accuracy.

Physically and strictly mathematically, the floodwater motion is coupled with the ship motion and the coupled equations of ship and floodwater motions should be solved simultaneously. The determination of the time varying mass of accumulated water (a fluid with infinite degrees of freedom) demands also an analogous effort to the set level of accuracy. When local flow characteristics are of interest, like impact loads occurring with heavy fluid sloshing, then a fine analysis of the flow is necessary. However, when the impact of the internal water on the ship motion is investigated, then it is only necessary to properly model global internal water motion and interaction effects and secondary local flow characteristics can be disregarded. Following this type of approximation the floodwater dynamics methods incorporated in numerical ship motion simulation methods can be substantially speeded up, a necessary characteristic when aiming to achieve practical simulation times.

The present paper is focusing on the floodwater dynamics modelling employed in the NTUA-SDL simulation method and demonstrates some viability aspects. The method addresses the motion of the floodwater by exploiting the 'lump mass' concept and achieves reliable predictions at comparably low computational time. Some typical comparison results between the employed simulation method and systematic relevant model experimental data, obtained from tests performed at the CEHIPAR Experimental Centre (El Pardo, Madrid) provide evidences regarding the validity range of the numerical method. Furthermore, a detailed focusing on the interaction force between the ship and floodwater is attempted comparing the interaction forces predicted by the simulation method for the sloshing inside a rectangular tank mounted on the deck of a vessel with those derived when a 2D RANS solver is employed. The presented results indicate that the employed approximate modelling properly captures the dominant part of the force, explaining in that way the method's effectiveness regarding the global motion behaviour of the flooded ship.

2. THE NUMERICAL SIMULATION METHOD

A suitable mathematical model accounting for the ship motion in the presence of water on deck has been developed at the Ship Design Laboratory of NTUA, and it is implemented with the computer code CAPSIM. It provides an efficient way to investigate the motion of the coupled system consisting of the ship and a flooded water mass as well as the stability of the overall system. The model is truly nonlinear allowing the consideration of large amplitude motions and the stability of the vessel in extreme environmental conditions.

The flooded ship, herein consisting of the intact ship with the presence of trapped water on deck, is considered as a two mass system, namely that of the intact ship and that of the flooded water. Further, the ship is considered as a rigid body having six degrees of freedom, while the floodwater is approximated by the lump mass concept, namely a mass being concentrated in its center of mass with three degrees of freedom.

The equations of motion of the coupled ship-water mass system can be derived by application of momentum conservation theorem, namely by considering the linear and angular momentum of the ship and the linear momentum of the lump mass that models the floodwater. Relevant equations are of the following general form:

$$\frac{d}{dt}\int_V \rho \vec{U} dv = \vec{F} \tag{1}$$

where ρ is the mass density of the volume V occupied by the ship-floodwater system, U is the local velocity and F is the sum of the external to the system applied hydrodynamic and other forces. In case of the angular momentum equation, linear momentum and forces are replaced by angular mass momentums and moments respectively.

The left hand side of these equations represents the kinematics of the system's mass, which can be exactly formulated and numerically treated. Obviously these terms depend on the coordinate system with reference to which they are defined. The body fixed system having its origin at the ship's center of mass G, has been used for the subsequent analysis. Relevant inertia terms of the rigid ship remain constant with respect to this reference system and the equations of motion can be greatly simplified. Following some algebraic manipulations (see [6], [7]), the following equations are derived, which represent the linear and angular momentum equations of the 3D rigid ship, along with the linear momentum equation of the lump mass of water:

$$m_s\left(\dot{\vec{U}}_G + \vec{\omega} \wedge \vec{U}_G\right) = \vec{F}_s \tag{2a}$$

$$[I]\dot{\vec{\omega}} + \vec{\omega} \wedge [I]\vec{\omega} = \vec{M}_s \tag{2b}$$

$$m_w\left(\dot{\vec{U}}_G + \dot{\vec{v}}_w + \vec{\omega} \wedge \left(\vec{U}_G + \vec{v}_w\right)\right) = \vec{F}_w \tag{2c}$$

where the subscripts s and w refer to the ship and flooded water respectively. While m denotes the masses, $[I]$ is the matrix of ship moments of inertia, U_G the linear velocity of G, ω the angular velocity of the ship, v_w the linear velocity of the water, F and M the external to each mass forces and moments. Dot over vector denotes differentiation with respect to time.

These equations are supplemented by a set of equations relating the velocities to the time rate of change of relevant position vectors. Therefore, an overall system of eighteen first order, nonlinear differential equations for the linear and angular velocities of the ship and the linear velocities of the floodwater's centroid is derived. If the external forces, acting on each system's mass, are known in advance, then the motion of the coupled system can be calculated by integration of the set differential equation system.

Let us assume that the two masses are interacting through an inherent to the system interaction force. Obviously this force is also part of the external forces acting over each mass. The right hand side of the set equations (2) actually includes this interaction force and its corresponding moments. Consequently, if this force is known then the coupling between the two masses can be determined and the coupled system is fully defined. Of course, this force is not known beforehand but it has to be determined along with the remaining motion quantities in the course of the overall solution procedure.

A common way to determine a force is to determine its resulting motion effect on the mass it acts, and vice versa: *assuming the motion of the mass centroid known, the force acting on it can be also determined.* The way to achieve the above with reference to the present flooded ship motion is to describe, to the extent possible exact, the flooded water mass motion. The interaction force can be now approximated if we assume that the water mass centroid moves along a known geometric domain. In particular, the free surface of the flooded water inside a ship's compartment, often a rectangular tank, follows a complicated wavy pattern, depending on the tank's geometry, the filling rate, the frequency and amplitude of oscillation. However, for the purpose of the present modeling, aiming at determining satisfactorily the coupled system's motions, it is sufficient to assume that the free surface of the flooded water remains always plane, but freely moving inside the tank, namely without a specific orientation.

Based on this assumption, the center of the floodwater mass at any particular position of the internal water free surface is moving along a unique surface path S_w, Figure 1.

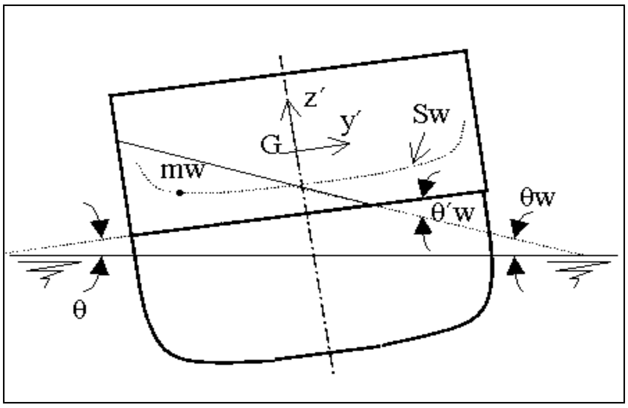

Figure 1 Definition of the domain of the floodwater mass centroid

The plane free surface forms an angle θ_w with the still water free surface of the sea, whereas the ship may experience a different angle θ.

This surface S_w is the geometrical locus of the floodwater's centroid path. Considering that the water's centroid moves over this known surface, then the interaction force can be calculated in a straightforward way, namely as following.

Assuming that the flooded water velocity is always tangential to the water surface S_w, we obtain the next kinematic condition, [6].

$$\vec{v}_w \cdot \vec{n}_{sw} = 0 \quad (3)$$

where n_{sw} is the normal to the surface unit vector.

Equation (3) together with an equation for the orientation of the interaction force itself fully defines the remaining set of equations for the interaction force calculation.

The external to the system acting forces and moments appearing on the right hand side of equations (2) express the entire set of forces acting on the present inertia system and causing its motion. These forces may be subdivided into seaway and wind force components; others might be added in a straightforward way (current forces, etc). Wave exciting forces, as the dominant dynamic part, can be further analyzed into Froude-Krylov or incident wave, radiation and diffraction forces, following linear potential theory. It is acknowledged that higher order effects (like drift forces, second-order Froude-Krylov, radiation and diffraction forces) could be considered by the same herein applied concept, following earlier works [3], [4], [13].

Incident wave forces together with the hydrostatic ones are herein calculated through direct integration of the dynamic and hydrostatic pressure over the instantaneously wetted surface of the vessel, defined by the undisturbed incoming wave. Radiation forces are herein calculated by the added mass and damping coefficients, calculated in frequency domain and properly transformed into the time domain applying the impulse response function concept by Cummins, [2].

$$F_{R,i}(t) = -A_{ij}(\infty)\dot{U}_{Gj} - \int_0^\infty K_{ij}(\tau)U_{Gj}(t-\tau)d\tau \,,\; i,j=1\div 6 \quad (4)$$

where A_{ij} are the added masses for infinite frequency of oscillation and the kernel functions K_{ij} are calculated by the cosine Fourier transform of the damping coefficients calculated in frequency domain. Elementary diffraction forces corresponding wave frequencies of an assumed irregular seaway spectrum are taken to be directly proportional to the corresponding elementary diffraction forces calculated in frequency domain. Finally, the consideration of nonlinear roll viscous effects is herein accomplished by using a quadratic roll velocity model, with semi-empirical damping coefficients. The time rate of change of the floodwater has been approached by use of Bernoulli's equation, modified by a semi-empirical, weir flow coefficient to account for the local flow effects at the damage opening.

Obviously, the successful motion simulation depends equally on the proper modeling of the left hand side of the set system of equations (2), namely the inertia terms, but also on the valid modeling of the right hand side, namely the external forces. It is essential to dispose an efficient method to provide accurate information on the exerted wave forces. Radiation and diffraction forces in the frequency domain were herein calculated by applying the computer code NEWDRIFT, [5]. It is a six DOF three-dimensional diffraction theory program for the calculation of motions and wave induced loads, including drift force effects acting on arbitrarily shaped bodies in regular waves. The code is based on a zero-speed Green function pulsating source distribution method and employs triangular or quadrilateral panels for the discretisation of the wetted ship surface.

In summary of the above, a complete system of differential equations accounting for the motion of the coupled system of ship and flooded water has been defined. It consists of the equations of momentum conservation, the relations between the velocities and the time rate of change of position vectors and finally a kinematic condition for the flooded water surface and the orientation of the interaction force. Hydrodynamic forces are calculated by use of the Impulse Response Function concept based on linear potential theory results for the added mass and hydrodynamic damping, the model considers however fully the non-linearities of ship hydrostatics, of the Froude-Krylov undisturbed wave forces and the viscous roll motion effects.

3. VALIDATION OF SIMULATION METHOD

Numerical simulation methods have been increasingly accepted in damage stability assessment by testing a series damage scenarios. The objective of the methods is to predict the ship motion and instabilities in extreme seaway. When validating such a simulation method, the flooded ship dynamics in stable conditions should be firstly ensured before concluding on the suitability of the method in marginal cases, where instability can occur.

A series of validation studies has been carried out by NTUA-SDL providing evidences about the suitability of the adopted modelling and the efficiency of the proposed damage stability assessment method. In this paragraph the comparison between theoretical and experimental results, derived by a recent NTUA-SDL study, are presented providing a representative overview of the suggested flooded ship modelling.

A series of tank model experiments were set up at the CEHIPAR model tank (El Pardo, Madrid), aiming to validate corresponding systematic numerical studies performed by the code CAPSIM. The motion of the studied model was reduced to three degrees of freedom, namely sway, heave and roll. The other degrees of freedom were restrained as their influence for this type of study is of lower significance, but herein additionally in order to exclude uncertainties associated with the validation of the experimental measurements, when the model is kept in beam seas.

The tested model was a passenger/Ro-Ro ferry, with its particulars presented in Table 1 and its body plan in Figure 2.

	MODEL	SHIP
Model scale	1:30	
Lpp	5.333 m	160.0 m
B	1.014 m	30.42 m
T	0.220 m	6.60 m
Dcar	0.308 m	9.25 m
Displacement	801 kg	21600 kg
GM	0.153 m	4.60 m

Table 1 Passenger/Ro-Ro ferry particulars

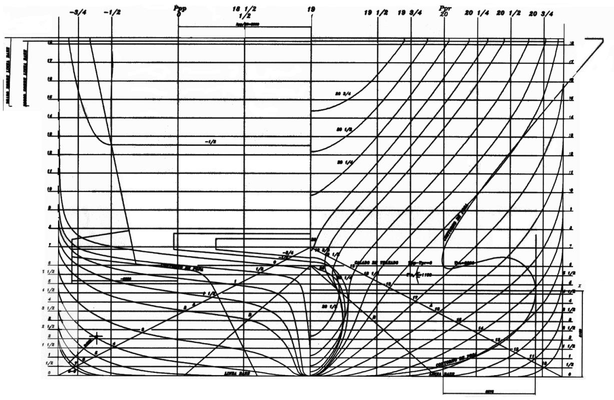

Figure 2 Passenger/Ro-Ro ferry body plan

The model was free to move only in three degrees of freedom that of sway, heave and roll, using a purposely developed restrain system, see [8]. Incoming waves were beam seas and the model could drag downstream under the effect of waves. The model was tested both in regular and irregular waves and both with open and closed damage opening above the main deck. Damage opening width was according to the SOLAS'95 provisions. In the tests with closed damage opening at the height of the car deck, constant amounts of water on the deck were reproduced. The whole damaged space consisted of two compartments, namely the engine room located in the model's after half, extending between stations 2.50 up to 3.75, and the car-deck garage room, extending above the main deck.

The increased metacentric height *GM* selected for the tests permitted testing with increased amounts of water on deck while ensuring stable conditions. The model could achieve in all tested cases a steady state condition after some time period and did not capsize.

In Figure 3 and Figure 4 the roll response of the model in regular wave conditions as a function of the incoming wave frequency is presented, as derived from experiments and the numerical simulation respectively. The damage opening above the main deck was herein closed and three different amounts of water in the garage are presented, namely 0, 40 and 60 kg.

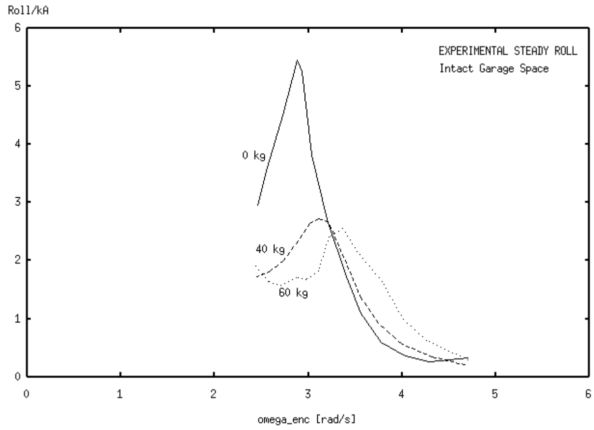

Figure 3 Experimental steady state roll response with closed damage opening at the garage

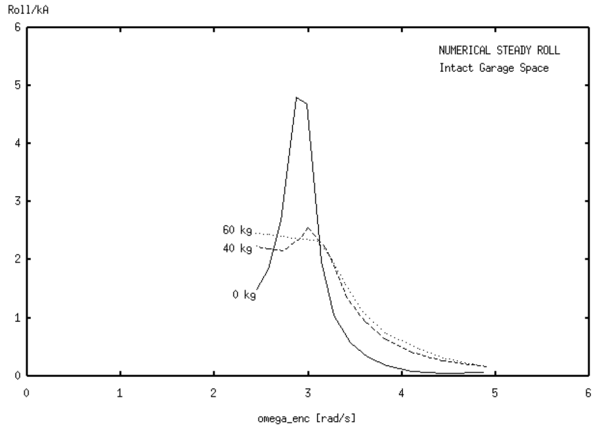

Figure 4 Numerical steady state roll response with closed damaged opening at the garage

As observed from the above two diagrams there is in general a good correlation of results for the behaviour of the flooded model between the experiments and the numerical simulation, and particularly for the change of behaviour in the presence of water compared to the case without water on deck. The effect of water on deck on the model roll motion seems like a clear increase of damping as well as a slight shift of resonance towards the higher frequencies. As a consequence of that shift the increase of roll response at higher frequencies with respect to the case without water on deck is apparent.

Numerical results predict a quite similar behaviour indicating a successful approach to the deck floodwater to ship interaction for these tests, despite the fact that the differences between the 40 kg and 60 kg flooding is less clear in the numerical simulation.

In Figure 5 and Figure 6 the corresponding behaviour of the model for the case of damaged garage, namely opening extended unlimited upwards, is presented for the experiments and the numerical simulation respectively. Three different wave slopes were herein tested, namely 1:30, 1:40 and 1:50.

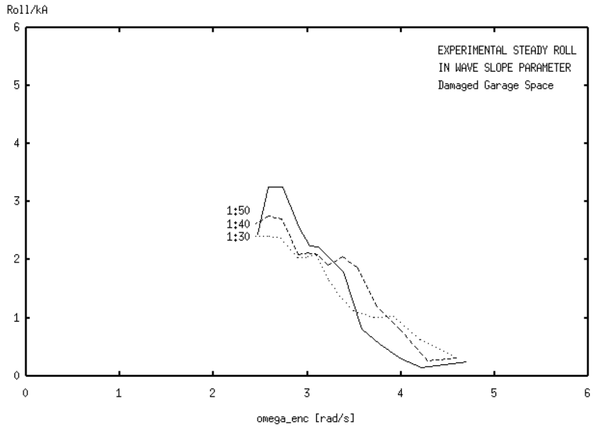

Figure 5 Experimental steady state roll response with open the damage opening at the garage

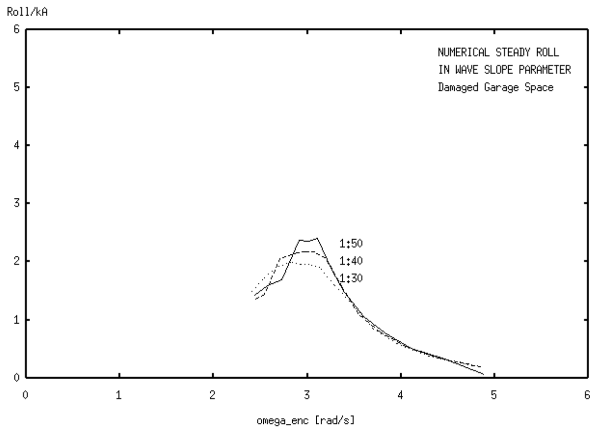

Figure 6 Numerical steady state roll response with open the damaged opening at the garage

In these tests the water could freely flow into and out the garage room through the damage opening. In the resulting steady state conditions, it was observed that in the mean some amount of water accumulated on the deck. As seen from the above diagrams, this appears to be quite independent of the incoming wave slope. A similar behaviour is observed in the numerical tests, particularly for the higher frequencies where a clear independency of wave slope is observed. In these tests the hydraulic modelling of water inflow and outflow was introduced, which was inactive in the previous tests with closed damage opening, Figure 3 and Figure 4. It is noted that proper modelling of the flooding procedure seems to be more important in the lower frequency range.

Reviewing the agreement of the experimental and numerical simulation results for the intact case, the trapped water case (closed damage opening) and the open damage opening case, it appears that the adopted modelling for the internal floodwater dynamics and the flooding through the damage opening is satisfactory for the practical assessment of the ship's roll motion in damage condition. Note that the investigation of the model performance in *regular* beam waves permitted a thorough understanding of the water on deck influence on the model motion and a good validation of the flooded ship dynamics modelling of the employed numerical code. The performance of the model in *irregular* beam waves, which is closer to reality, has been also tested in the second series of experiments, providing an additional global test for the developed numerical code.

Figure 7 and Figure 8 present the probability density of the roll motion for the case of incoming irregular beam waves corresponding to JONSWAP wave spectrum with significant wave height *Hs* = 4.05 m and two modal periods 8.05 and 12.07 seconds, defining short and long waves respectively.

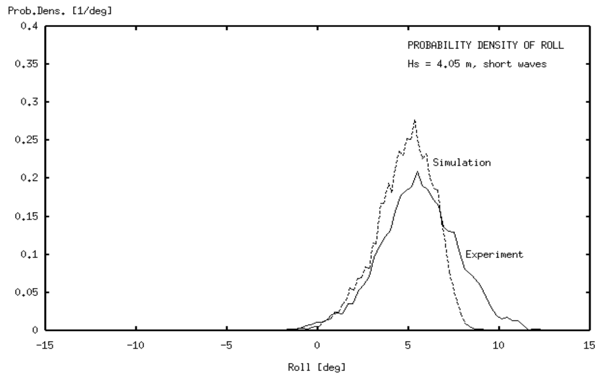

Figure 7 Probability density of roll in steady state response, short waves

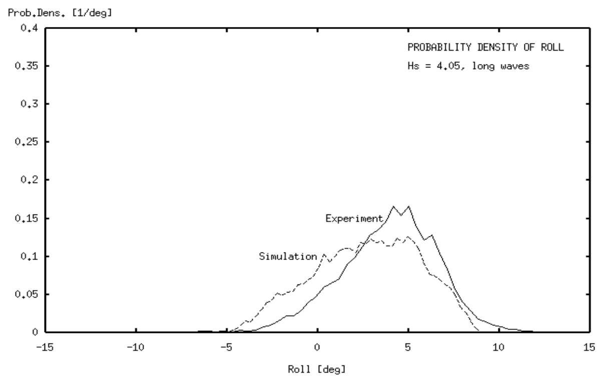

Figure 8 Probability density of roll in steady state response, long waves

Graphs of the probability density functions provide a clear view of the overall character of the irregular ship response, describing the different heeling levels the model could obtain for a given seaway. A good agreement between the experimental and the numerical-simulation results is observed. Short waves result to a density function of steeper peak while long waves to a wider one. A slight shift between the peaks of the numerical and experimental results can be observed for both the short and long waves. This shift in peaks could be due to differences in the amount of water finally accumulated on the car deck and the associated effects on ship's hydrodynamic behaviour.

The results presented so far provide evidences about the efficiency of the presently adopted modelling of the flooded ship and the incorporated floodwater dynamics. Further results concerning the validity of the NTUA-SDL numerical simulation method can be found into [6], [9], [10].

4. THE FLOODWATER–SHIP INTERACTION

A more detailed study focusing on the interaction between the ship and the floodwater motion is presented in the following. The general efficiency of the floodwater dynamics modelling, presented so far, is further investigated with the aim to better understand various aspects of this modelling, as well as to reveal practical application aspects. In particular, a detailed study has been carried out to more carefully investigate the coupling effects between the ship and the floodwater mass that can be expressed through a resultant interaction force. This interaction force was approximated both by the above described simplified numerical model for floodwater motion and also by use of a more accurate CFD-RANS code, and satisfactory agreement between the results of both approaches was observed.

Considering the two coupled masses, namely that of ship and that of the internal water, interacting with each other through an interaction force, namely the resultant of all forces exerted between them, this force is herein investigated for the case of a fishing vessel moving under the excitation of regular beam waves and having a partially filled rectangular tank on the weather deck.

For the present investigation of the floodwater motion effects the Navier–Stokes solver of the Ship & Marine Hydrodynamics Laboratory of NTUA was employed in parallel to the presently investigated simulation code CAPSIM, enabling the calculation of sloshing effects of water inside tanks. The employed RANS solver code is based on the control volume approach and solves the discretised, unsteady N-S equations in a non-orthogonal mesh, which is continuously varied in order to properly model the instantaneous free surface boundary, [12].

The vessel tested was a fishing vessel with water on deck trapped in a rectangular tank. This particular vessel has been tested in model basin [1], and the experimental measurements of the roll response of the vessel in regular waves with different constant amounts of water in deck tank were earlier presented.

More detailed investigations on the trapped water effects on the fishing vessel's motion were presented in [9] and [11] where a fine well correlation between numerical simulation results and experimental measurements for the ship roll motion was found. A number of test simulations were performed, for which the motion of the vessel was calculated. The internal flow of water inside the tank was also calculated by use of NTUA's Navier-Stokes solver, while the forcing of the vessel was according to the motion resulting from simulations with the code CAPSIM. Thus, two alternative approximations for the internal water motion, and the resulting interaction forces, were obtained, ensuring in both case the same ship motion. In the following, two representative tests are given revealing the characteristics of the presently adopted floodwater modelling.

The first case presented in Figure 9, Figure 10 and Figure 11 regards a tank breadth to water depth ratio equal to 25. In the second case presented in Figure 12, Figure 13 and Figure 14 the water depth is doubled giving a ratio equal to 12.5. Vessel in both cases is excited on to the same frequency sqrt(L/lambda) = 0.75, which corresponds to the roll resonance frequency of the intact fishing vessel, namely the ship without water in the tank. Whereas, the first natural frequency of the tank corresponding to the two filling rates is expected to be about 0.50 and 0.71 respectively. Therefore, the assumed forcing frequency is close to the theoretical first resonance of the second filling rate case and increased sloshing effects can be expected in this test case.

The forces and moments presented in the following are the force on the tank's sides, the force on the tank's bottom and the resultant roll moment exerted on the vessel by the two forces on tank's sides and bottom. The thick line in the diagrams corresponds to the CFD-RANS results whereas the thin one to the CAPSIM code.

The calculated side force, as shown in Figure 9 and Figure 12, has pronounced peak values for the CFD-RANS solver compared to the CAPSIM code. This behaviour, as can be seen in calculated RANS detailed flow calculations, is related to the impact loads occurring when the internal water hits the tank sides. The results for the force acting on the tank bottom, Figure 10 and Figure 13, are significantly better correlated as in this area the impact loads are greatly diminished. Obviously, this difference is the most remarkable between the two approaches.

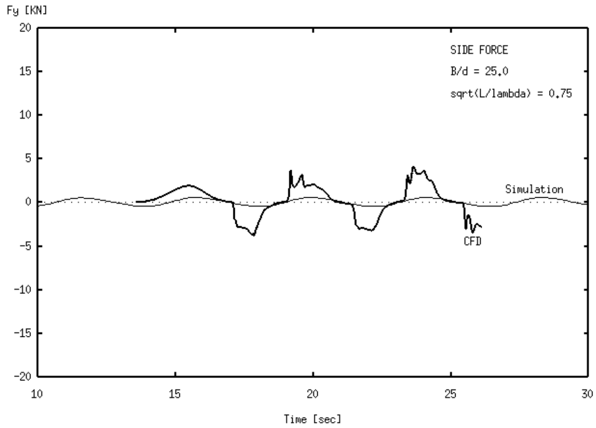

Figure 9 Force on tank side for shallower water

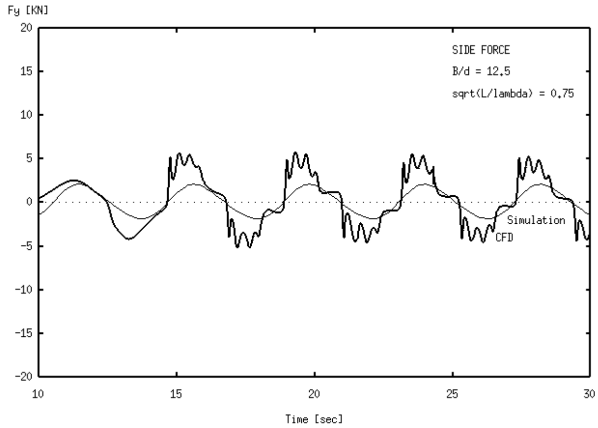

Figure 12 Force on tank side for deeper water

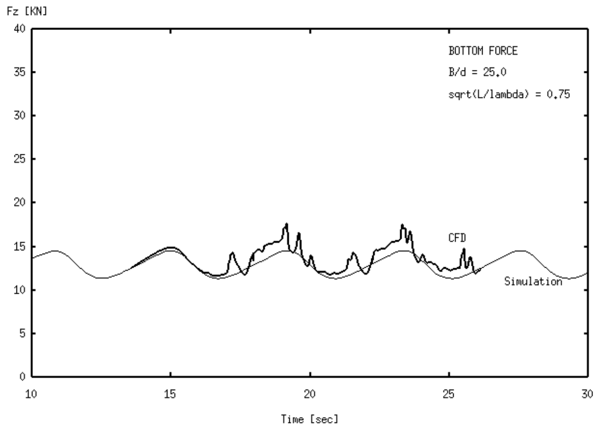

Figure 10 Force on tank bottom for shallower water

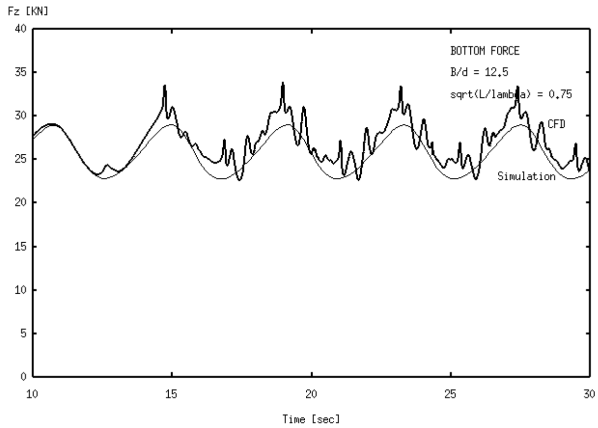

Figure 13 Force on tank bottom for deeper water

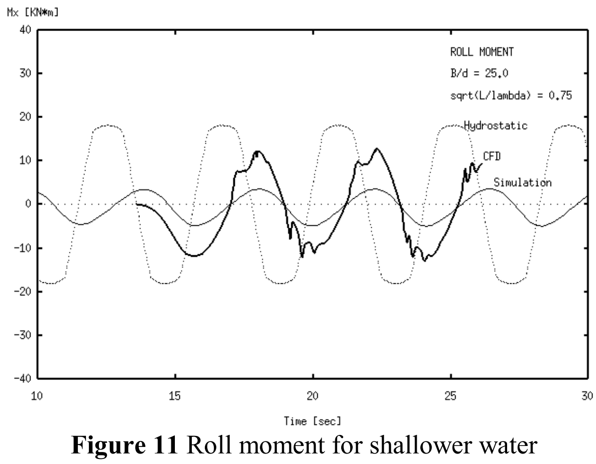

Figure 11 Roll moment for shallower water

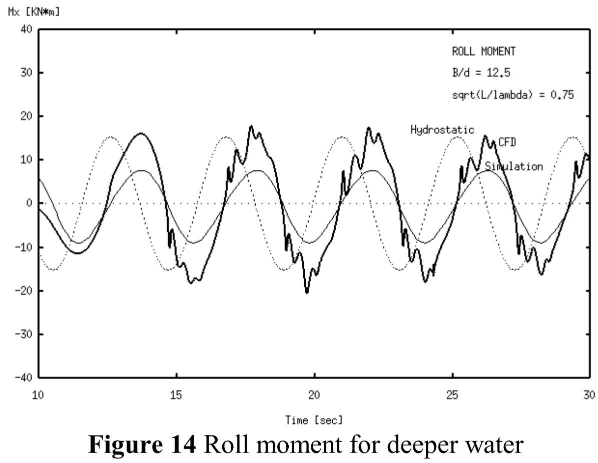

Figure 14 Roll moment for deeper water

The floodwater motion modelling employed in the CAPSIM code omits the free surface waves and related effects. However, the final effect on the ship motion is not so significant, as the impact load herein omitted is rather related to local loads and stresses and to a much lesser degree to any energy transfer to the ship.

Figure 11 and Figure 14 provide an overview of the actual physics of the studied problem. The roll moments calculated by the two methods are accompanied by the roll moment corresponding to pure hydrostatic calculations (represented by the dotted line). In particular, the hydrostatic moment equals the moment that would act on the vessel if the water in the tank, at each ship position, had a distribution corresponding to still water conditions. This static roll moment seems to be about 90 degrees out of phase of the other two moments. Motion simulation and CFD results are in phase, while the amplitude of the roll moment resulting from the simulation code appears underestimated as a consequence of the underestimation of the forces on the tank's sides.

As regards, the higher frequency oscillatory part of these results, shown in the diagrams as ripples, they are the result of the upper water layer disturbances. For the second case, which is closer to the tank resonance frequency, the ripples are increased.

The above-presented comparison of the interaction effects was repeated for other test cases. Perfect correlation is met for the higher frequency where the roll amplitude is diminished. The simulation and the CFD results seem almost identical. Following the results of these studied cases it can be concluded that the employed simulation method, associated with a simplified "lump mass" modelling of the internal water motion, provides a good approximation to the water to ship interaction forces. In particular, it seems that the prediction of roll interaction moment (amplitude and phase) is quite satisfactory and associated results of the simulated coupled ship and internal water motions can be expected to be reliable.

The employed numerical simulation method for the prediction of the coupled ship-floodwater motion appears quite efficient, at satisfactory accuracy, in terms of computing time. As shown in Table 2, the required CPU time of the motion simulation code is, compared to CFD-RANS code employed herein for comparison of the internal water motion effects, substantially lower. Note that the computing time given in the table for the CAPSIM code corresponds to the total computing time to solve the entire coupled motion problem, including ship's motion, whereas corresponding time for the CFD code is related only to the sloshing problem. The cited CFD times for the cases under consideration do vary, depending inversely on the oscillation frequency.

CODE	CPU Time / Simulation Time
CAPSIM	0.33
CFD sloshing	3440.00
	Processor Alpha 21264 64-bits 500MHz

Table 2 Computing Times

The above stated computing time requirements allow the practical application of the CAPSIM code to the assessment of the flooded ship motion dynamics. Low computing time at satisfactory accuracy is of paramount importance in this type of models, particularly when the vessel's behaviour for a large set of loading, damage and environmental conditions has to be studied, as requested by relevant damage stability assessment procedures.

5. CONCLUSIONS

In this paper, some recent results, regarding the numerical modelling of the floodwater dynamics developed at NTUA-SDL, are reported, providing good evidence for the practical applicability of this method. The method proved to be quite efficient when studying the ship motion dynamics and the interaction caused by the floodwater. The basic assumption of the modelling, namely the absence of waves on the free surface of floodwater, seems to have a low impact on the ship motion and it is rather related to the local impact loads on the tank walls.

The major advantage of the proposed method is its efficiency in terms of the achieved accuracy compared to computing time requirements. The drastic reduction in computing time requirements is paid by an acceptable loss of accuracy for the prediction of ship motion.

6. ACKNOWLEDGEMENTS

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