ON THE STABILITY OF FAST FERRY IN DAMAGE SCENARIOS

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SUMMARY

The ro-ro ships are characterized by a large garage compartment extending from stern to bow. Damage conditions, heavy weather and large floodable spaces could create serious accidents, with the loss of life and goods at sea, both for conventional ferries and fast ferries. The occurred accidents showed the need of a more accurate approach to the damaged ship stability in waves, also in head sea and following sea conditions, because of the great movements of water on the car deck. With this aim a tool for analysing the ship response in wave with damaged compartments has been developed and applied on a typical fast ferry. The ship dynamic is simulated in time domain, including non-linear effects, taking into account critical scenarios on the damaged ship. The applications regard ship grounding, assuming head sea, modelled by regular wave. In addition to that, also the particularly critical condition of a transversal wind heeling moment has been applied to compute non symmetrical behaviour. Moreover the stability problems arising from the presence of trapped water in the garage compartment are investigated assuming the same environmental scenarios.

1. INTRODUCTION

The primary purpose of a ship, especially for fast ferries, is to ensure the safety of human life at sea.

The first goal of a designer is to look at the passenger safety not only through the constraint rules of regulatory bodies but also through more refined design criteria. The current stability margins are based on the rule of classification society and international regulation: the high speed code applies to fast vessels, set apart from Solas standards (IMO 2009).

Anyway, despite the strict rules, several accidents involved conventional and high speed ferries. It underlines the need for a deeper approach assessing ship damage stability. In the event of damage, together with adverse weather condition, several ferries experienced loss of life and goods at sea. In particular the ro-ro ferry, in damage conditions, can be easily affected by fire or flooding for the entire length of the garage: this compartment usually has no kind of subdivision.

Ship damage stability in wave for ro-ro vessels should be investigated more in depth. Indeed, for this type of ship, the effect on stability due to water trapped in compartments characterized by high freesurface should be a sensitive problem that has to be investigated more in detail.

The potential accumulation of floodwater on the ro-ro deck space in case of damage was studied by several authors for conventional vessels (Jankowski & Laskowski 2006) (Carette & van Walree 2011) (Acanfora & Coppola 2013) (Santos & Guedes Soares 2006), while only recently some work pointed out the need to attribute this problem also to high speed ferries (Maimun et alt. 2011). In particular, the reference paper (Maimun et alt. 2011) deals with the development of a tool for assessing damage stability in beam sea for a fast vessel.

The dynamic behaviour of a ship in damage condition is characterized by highly non-linear effects; according to this, the use of time domain simulation seems to be the most suited technique to be applied to approach the problem. In the reference paper (Lee at alt. 2007) the authors developed a time domain theoretical model for the prediction of damaged ship motion and accidental flooding in waves. They also provided comparison with experimental tests on a conventional roro-pax model. Nevertheless the effects of the wave pressure on the flooding were not investigated.

The main goal of this paper is to develop a numerical method, in order to evaluate the ship wave response in the presence of damaged compartments, for a fast ferry.

The method is based on 6 degrees of freedom (6DoF) equations of motion, for the intact ship in head or following seas. It has also the possibility to take into account beam wind actions. The extended superstructures that characterize this type of vessels could lead to a huge wind heeling moment, responsible of non-symmetrical response of the ship during the flooding.

The damage simulations were carried out for a ship grounding scenario, with and without wave: in the latter case the dynamic pressure, together with the static head of water on the ship damage hole, was assumed in evaluating the flow rate during the flooding of the compartments. The ship's behaviour with a fixed amount of water trapped on the garage deck has been also analysed.

The water within the flooded compartments has been implemented in the numerical simulation according to the lumped mass model (Manderbacka et alt. 2011).

The non-linearity due to the hull geometry and to the compartment shape are fully taken into account: in particular the geometrical tank properties are evaluated as a function of the water height within the compartment and implemented in the simulation by means of lookup-tables.

The ship model used for the applications represents a typical ferry operating in the "bay of Naples".

In the next sections the equation of motions of the ship and the flooding model are presented. The first applications carried out, are intended to test the reliability of the developed method by checking the transient stages and the equilibrium positions of the ship model, in still water. Moreover the heave and pitch responses, in longitudinal regular waves, obtained from the numerical simulation, have been compared to linear sea-keeping data for the same ship.

Finally the aforementioned damage stability applications are presented and discussed.

2. THE NUMERICAL MODEL

The equations of motion for a ship refer to a body fixed co-ordinate system, centred at the initial vessel's centre of gravity G.

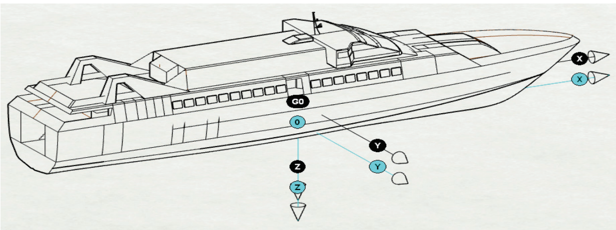

Figure 1. Body fixed and inertial co-ordinate systems

The earth fixed axes, instead presents the X-Y plane coincident with the still water level. These two reference frames are shown in Figure 1.

The equations describing the 6DoF dynamic model for a damaged ship, regarded as a rigid body, are presented below (1):

$$m\left[\dot{\mathbf{u}}+\boldsymbol{\omega}\times\mathbf{u}\right]=\mathbf{f}_{\text{ext}}+m\mathbf{g}-\mathbf{f}_{\text{i}} \quad (1)$$

$$\mathbf{I}\dot{\boldsymbol{\omega}}+\boldsymbol{\omega}\times\mathbf{I}\boldsymbol{\omega}=\mathbf{m}_{\text{ext}}-\mathbf{r}_{\text{i}}\times\mathbf{f}_{\mathbf{i}} \quad (2)$$

$$\begin{aligned} &m_{\text{i}}\left[\dot{\mathbf{u}}+\boldsymbol{\omega}\times\mathbf{r}_{\text{i}}+\boldsymbol{\omega}\times\left(\mathbf{u}+\boldsymbol{\omega}\times\mathbf{r}_{\text{i}}\right)+\right.\\ &\left.+\dot{\mathbf{u}}_{\text{i}}+2\boldsymbol{\omega}\times\mathbf{u}_{\text{i}}\right]+\dot{m}_{\text{i}}\left(\mathbf{u}+\mathbf{u}_{\text{i}}+\boldsymbol{\omega}\times\mathbf{r}_{\text{i}}\right)=\mathbf{f}_{\text{i}}+m_{\text{i}}\mathbf{g}\end{aligned} \quad (3)$$

According to (Manderbacka et alt. 2011) ship motions are solved from the equations (1) and (2) based on the conservation of momentum, while the flood water is modelled as a lumped mass (3); the damage is simulated assuming the added water method.

In the external forces and moments, the radiant actions, i.e. added mass and damping terms, the non-linear buoyancy actions, and the wave loads, i.e. Froude-Krylov and diffraction actions, figure.

The simulation model works on a discrete representation of the hull, using triangular panels. The non-linear restoring generalized forces and the Froude-Krylov wave loads are evaluated, at each time, on the instantaneous ship wetted surface. Radiation and diffraction forces are derived using a linear model.

The intact ship numerical model, implemented in Matlab/Simulink, is based and derived on the same method reported in (Matusiak 2013). For the purpose of the application, head sea, modeled with regular sinusoidal wave, is assumed.

The developed method for damage stability simulations, i.e. for grounding scenario and for not drained water in the garage compartment, is carried out in the next subsections. The radiation actions on the vessel are assumed to be constant, referring to the initial intact ship floating position also in case of damage.

2.1 DAMAGE ASSUMPTIONS

Ship grounding for a fast vessel represents a dangerous damage situation, as also mentioned by the rules (RINA 2009).

The damage simulation has been carried out by applying the water loading method: the implemented model is capable to evaluate the flow rate of the water through the damaged hull as function of the instantaneous water height above the tank. The quantity of water m_i that floods the interior compartment can be obtained from the following formula (Santos 2002) (Mironiuk 2010):

$$m_i(t)=\rho\int_0^t A_0K\sqrt{2g(Z_c-Z_{c0})}dt \quad (4)$$

where the constant K is assumed equal to 0.6.

The abovementioned formula was developed from the Bernoulli theorem assuming p=0:

$$gh+p+\frac{1}{2}v^2=C$$

In this research work, the flow rate formula has been developed for analyzing the flooding condition of a damaged ship in wave. Assuming the presence of a regular sinusoidal wave, the wave pressure p should be taken into account by means of Froude-Krylov formula:

$$p=g\xi e^{-k(Z_c+\xi)} \quad (5)$$

Therefore the equation (4) has been modified as follows and implemented within the numerical simulation:

$$Q(t)=\rho\int_0^t A_0K\sqrt{2g\left(\xi e^{-k(Z_c+\xi)}+Z_c-Z_{c0}\right)}dt \quad (6)$$

Furthermore, within the simulation, the possibility of water spillage from the compartment has been introduced, if the head of water within the tank is:

$$Z_{c0} > \xi e^{-k(Z_c+\xi)} + Z_c \quad (7)$$

This relation can be satisfied, after the transient stage of flooding, when the wave through is passing above the damage hole.

The damaged compartment geometry is described by means of volumes and center of volume of the flooding water, implemented as look-up table within the numerical simulation model. The motions of the water within tank are assumed to be quasi-static, meaning that at each time the freesurface remains horizontal in the inertial frame. This assumption, in carrying out the applications, led also to neglect the acceleration of the lumped mass $\dot{\mathbf{u}}_i$.

3. THE SHIP MODEL

For the purpose of the applications, an example fast ferry has been used. The ship complies with the main standard practices for the Ro-ro pax mono –hulls and the subdivision for this vessel has been designed in order to satisfy the HSC code 2000/2009 damage stability criteria.

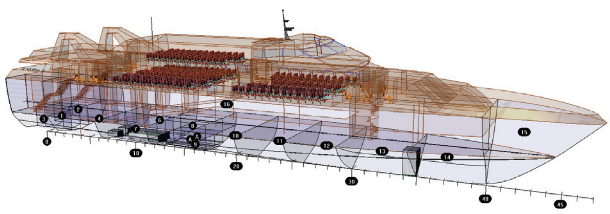

Figure 2. 3D view of the ship subdivision.

The 3D view of the ship is shown in Figure 2: it represents a typical ferry operated in the “bay of Naples.

In all the carried out applications, the full loading condition is assumed; the main characteristics of the ship are listed in Table 1.

Table 1. Main characteristics of the ship

L_{OA}	71.06 m
L_{WL}	64.54 m
B	13.40 m
D	8.5 m
Δ	650 t
VCG	5.17
GM	2.32
N° pax	530
N° ro-ro	40
Range	350 NM

All the damage scenarios of the sample vessel have been investigated according to the HSC code 2000/09 in a previous research work (Acanfora et alt. 2011). The sample damage condition assumed for the application is shown in Figure 3: it represents a damage scenario in the area vulnerable to raking damage (see Table 2), in the forepart of the vessel. This damage condition was also chosen in order to focus on the capability of the model in dealing with changes of trim during the flooding.

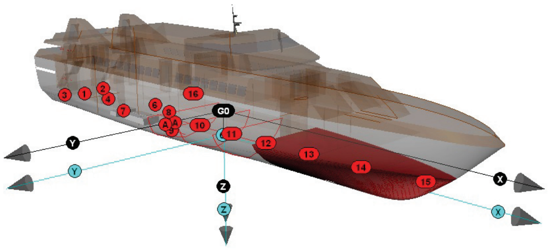

Figure 3. Raking damage condition

Table 2. Bottom damage dimensions

Areas vulnerable to raking damage HSC 2000/09			
l_1 (55%L) (m)	*l_2 (m)*	*p (m)*	*g (m)*
35.48	22.58	0.35	0.87
Areas not vulnerable to raking damage HSC 2000/09			
l (m)		*p (m)*	*g (m)*
4.95		0.17	1.74

4. APPLICATIONS

4.1 PRELIMINARY CHECK

The main goal of this research work is the development of a numerical simulation model capable to predict the dynamic behaviour of a damaged fast ferry, in presence of longitudinal sea and heeling actions due to the wind.

Due to the lack of experimental tests on the ship model, preliminary numerical applications have been carried out in order to assess the reliability of the results. The comparison of the results was performed with well-known numerical codes.

The initial ship equilibrium condition, for all the carried out computations, is assumed to be even-keel with a draft of 2.315 m, corresponding to the full loading displacement (see Table 1).

4.2 DECAY TEST

The first check, carried out on the intact hull, regards the ship response to initial perturbation for heave, pitch and roll. These tests are intended to analyse the transient stage of the dynamic system, mainly regarding damping actions.

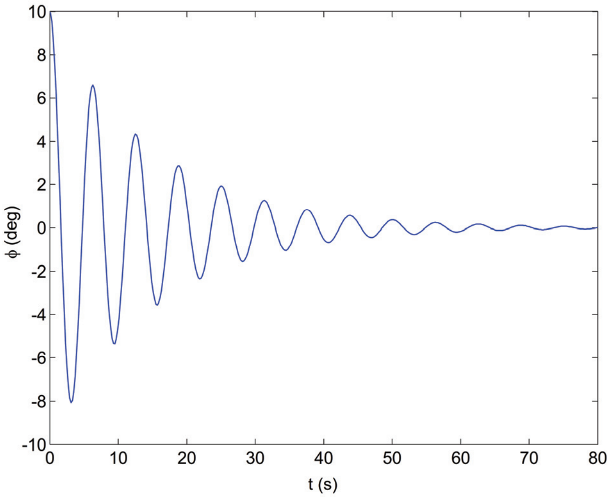

Figure 4. Roll decay test.

The roll decay test in the numerical simulation model was performed assuming an initial heeling perturbation of 10° (see Figure 4); while, for the pitch decay test, a smaller value for the perturbation was set at 2° (see Figure 5). For the heave decay test, instead, the ship was assumed to be initially over-immersed of 0.20 m (see Figure 6). For clarity, the *z* value of Figure 6 is defined, in the inertial frame, as the vertical distance of the centre of gravity from the water-plane: a negative value of the *z*, means the CG above water.

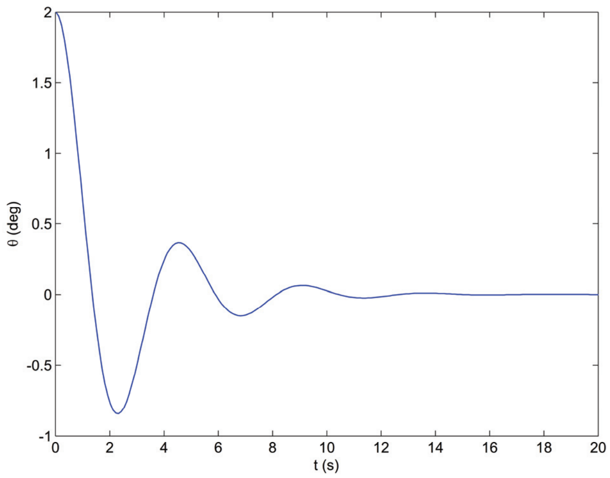

Figure 5. Pitch decay test.

From the obtained results it is possible to notice that the qualitative behaviour, of the several motion decay tests, seems to agree with the expected theoretical overall behaviour (Crossland et alt. 1993). The heave and pitch responses present faster decay time than the roll response with a sudden damping of the oscillations: this is in accordance with the lower damping that characterizes the ship roll motion.

In addition to the decay test, also step response test was performed in the simulation, for checking the roll behaviour of the implemented numerical model. The step response result is shown in Figure 7, obtained applying to the ship a step heeling model of about 1500kNm. The transient stage presents the overshoot that is almost two times bigger than the final equilibrium value of 5.76°:

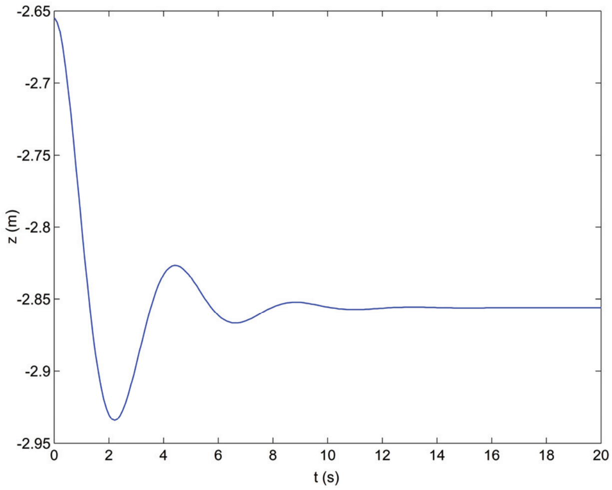

Figure 6. Heave decay test.

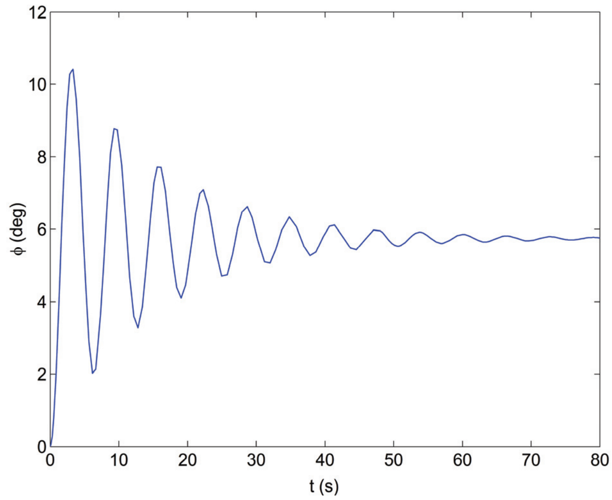

Figure 7. Roll step response.

Also this final equilibrium value has been checked, by means of the hydrostatic code "Autohydro": for the same condition the equilibrium was reached for a heel angle of 5.73°.

4.3 DAMAGE STABILITY AND LOLL ANGLE

The last applications, regarding the reliability of the results, obtained from the developed and implemented numerical method, were carried out in evaluating the final equilibrium after damage. Moreover, the angle of loll was evaluated, introducing an amount of water in the garage compartment: this condition leads to an initial negative GM, due to the high freesurface moments.

Assuming the grounding damage scenario shown in Figure 3, for the full loading initial condition, the final equilibrium after flooding was obtained both from the developed simulation and from Autohydro. In Table 4 is reported a comparison between the results obtained by applying the two aforementioned approaches.

Table 4. Bottom damage, final equilibrium comparison: hydrostic code (Ahydro) vs time domain simulation.

Variable	Ahydro	Simulation
Flooded water	612.2 t	611.6 t
Initial trim	0°	0°
Final trim	-3.13°	-3.125°
Initial *z*	-2.856 m	-2.856
Final *z*	-1.919 m	-1.920

As could be noticed the comparison shows a good agreement regarding the final stage of equilibrium after flooding. In performing the dynamic simulation in the developed code, an effective damage hole of 3 m^2 was assumed located across the damaged compartments. The head of water, in evaluating the hydrostatic head of water, was obtained as the mean value of the pressure at the ship bottom, in the zone of the damage hole. The time domain results for the simulation, reported in Table 4, are shown in the next section in Figure 12.

The numerical simulation is intended for analysing the effect of water trapped in compartment characterized by high free-surface moments. For checking the capability of the system to deal with negative GM conditions, the angle of loll was evaluated within the simulation and compared with Autohydro results.

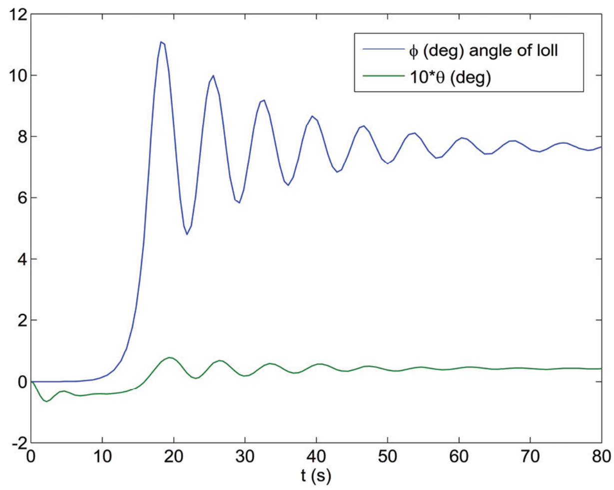

Figure 8. Loll simulation.

The amount of water trapped in the garage was set to a sample value of 50 t corresponding to 0.086 m of water on the deck, for the ship in even-keel position. From the hydrostatic computation the vessel shows a negative metacentric height i.e. GM=-6.384 m, that leads to a loll angle of 7.84°, together with a trim angle of 0.05°.

In Figure 8, the time domain results from the developed simulation model are presented. The final equilibrium results are respectively 7.653° for the angle of loll and 0.042° for the trim angle due to the loll. Also in this case a good agreement with the known hydrostatic code was achieved.

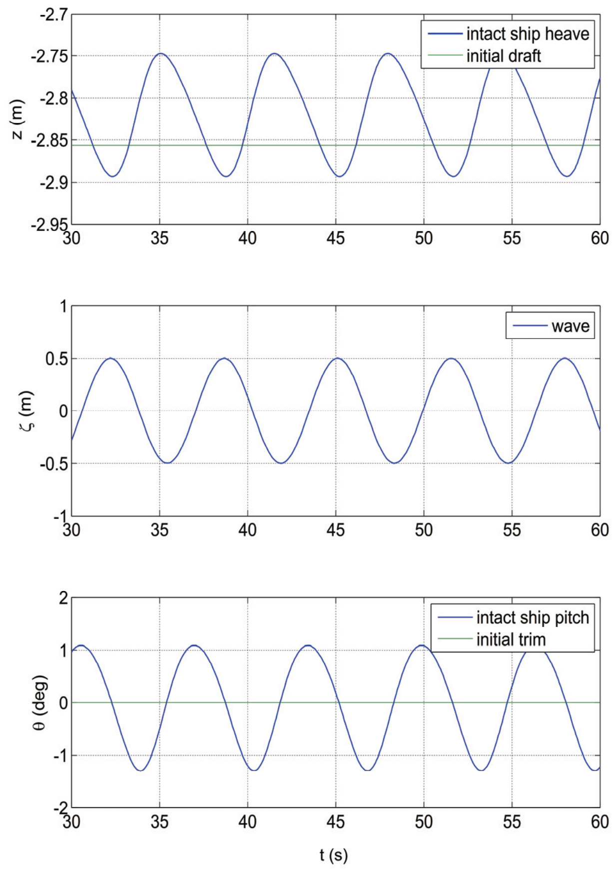

Figure 9. Intact ship in wave simulation.

5. INTACT SHIP DYNAMIC BEHAVIOUR

In this section the calculations regarding the behaviour of the intact ship in wave are presented; the results obtained by the implemented non-linear simulation for the intact ship are checked, before applying the damage analysis.

This check was performed by comparing the non-dimensional responses obtained from the numerical simulation, for several wave frequencies and amplitudes, with linear seakeeping responses (Faltinsen 1990). The heave and pitch comparisons are shown respectively in Figure 10 and 11.

The carried out comparison shows a good agreement between the developed method and the linear seakeeping results.

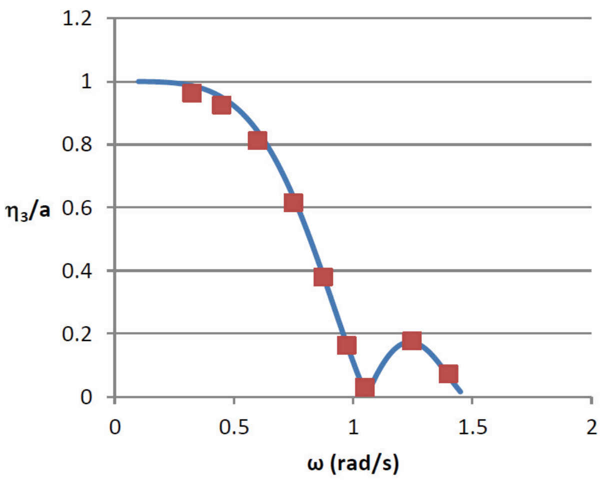

Figure 10. Heave response comparison.

In both Figures 10 and 11 the continuous line represents the response amplitude operator (RAO) for heave and pitch motions, obtained by a linear potential code, while the discrete points represent the amplitude, of the respective motion responses, from the simulation model. They are made non-dimensional using the correspondent wave amplitudes used in running the computations. The wave amplitudes were chosen in order to obtain significant motions, avoiding the weather-tight deck of the ship to be underwater.

The differences between the linear and the non-linear approach are more pronounced at lower frequencies, especially for the pitch (Figure 11). This is in accordance with the knowledge that at lower frequencies the non-linear Froude-Krylov forces prevail on the linear diffraction forces.

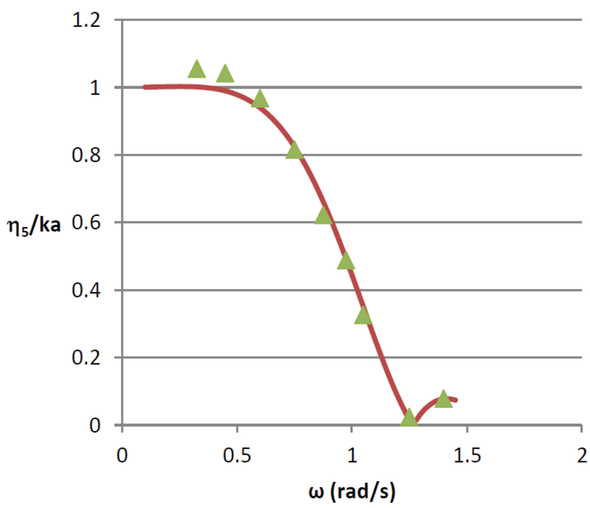

Figure 11. Pitch response comparison.

6. DAMAGED SHIP DYNAMIC BEHAVIOUR

The main results obtained from the numerical simulation for the ship in damaged scenarios, in longitudinal regular seas, are presented in this section. The wave chosen for the application is characterized by a frequency ω= 0.975 rad/s that leads to a wave length λ equal to the ship length. The amplitude is a = 0.5 m, the propagation direction is β=180° (head sea).

In Figure 11 is given a sample of the intact ship motions (heave and pitch) in time domain, obtained from the simulation model, for the chosen wave. The wave profile is observed at the CG. The ship behavior in this condition shows a mean heave value above the initial draft, and a negative mean pitch, very close to zero; all this means that the ship is slightly over-immersed in the bow part and it could be mainly justified by considering the slender volume that characterizes this zone. Moreover from Figure 11 it can be noticed that the ship experiences the maximum over-immersion when the crest is located above the CG. At the same instant, instead, the pitch is presented close to zero.

Assuming the same grounding scenario reported in the next section, the damaged ship behavior was simulated both in presence and in absence of wave. The time history of the flooding with no wave actions (see Table 4 for the final equilibrium) is compared to the ship flooding behavior in head seas: the developed method, discussed in section 2.1, was applied.

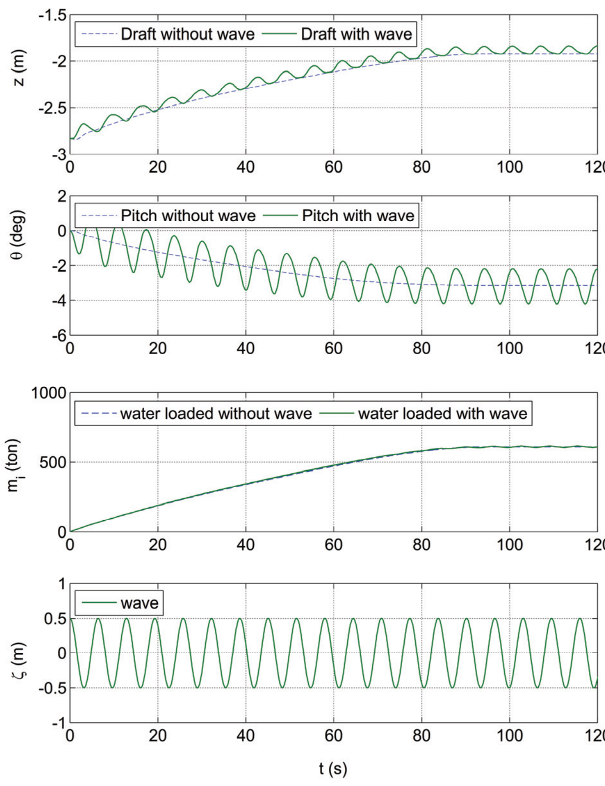

Figure 12. Ship grounding simulations.

In Figure 12 the results obtained by the numerical simulation, performed on this scenario, are presented. The dashed line represents the response for the transient stage of flooding in still water; as could be noticed from the details of Figure 13, the equilibrium condition is reached after around 95s. In introducing the wave effects on the flooding numerical simulation, it is possible to observe that the mean heave of the damaged ship seems to be above the draft time history with no wave. Moreover also in the damaged case the mean pitch in wave presents slightly below the damaged trim with no wave. This behavior follows what has already been observed for the intact ship in Figure 11.

In Figure 12, the amplitude of the pitch response in wave is small, with no significant difference with the intact amplitude response; the heave, instead is characterized by reduced amplitude compared to the intact one. This behavior can be attributed to the non-linearity of the restoring and Froude-Krylov actions due to the increase in draft and forward trim.

The water loading details, for the implemented model, taking into account dynamic pressure on the damage hole and spilling, are given in Figure 13. The dynamic equilibrium after flooding in wave seems to be reached later than the no wave condition; the water loaded has its maximum and minimum respectively close to wave crest and trough, within a range of almost 9 ton.

Finally the simulation results, regarding the effect of the water trapped on the garage deck, for the intact ship in wave, are shown in Figure 14. The sample amount of water used for the calculation is 50 tons; the constant heeling moment due to the lateral wind is set at 1500 kNm. The ship behavior for this condition, with trapped water, is also compared to the results for the same condition but with no water (dashed line in Figure 14).

From the carried out simulations it is possible to notice how the water presence in the garage compartment leads to a mean roll value almost two times bigger than the case with no trapped water, to increased pitch motions; to slightly dampen heave responses. Figure 14 also reports by a dashed-dot line, the heel angle at the equilibrium, with water trapped and lateral wind moment and no wave. It is possible to notice how the mean rolling value is few degrees lower than the static value, due to the sloshing motions within the compartment.

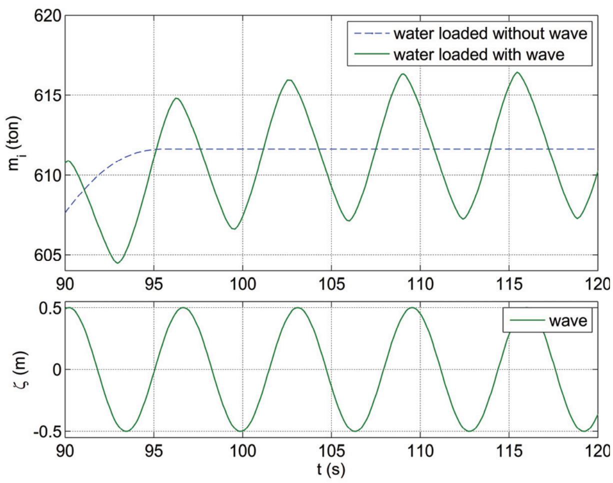

Figure 13. Details of the ship flooding in wave simulation.

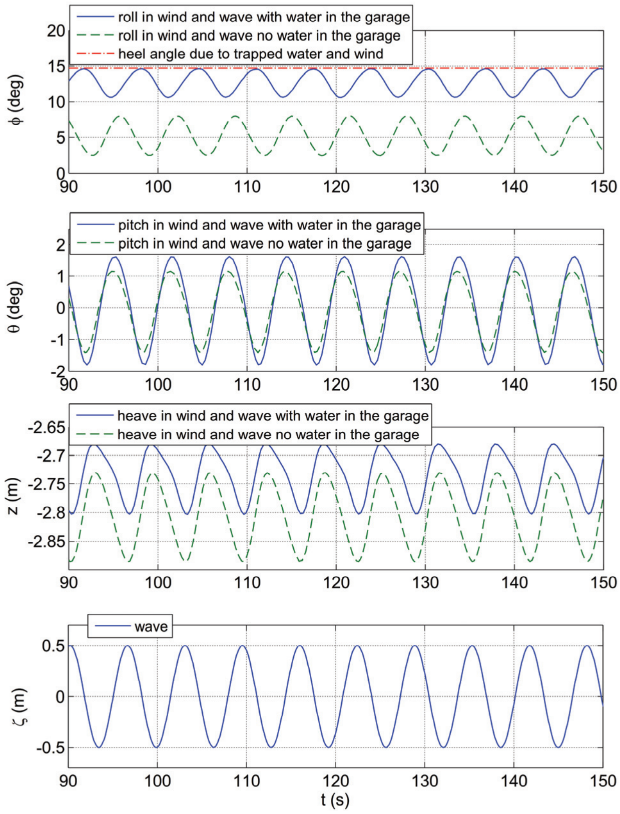

Figure 14. Ship behavior with and without trapped water.

7. CONCLUSIONS

The paper presents the development and the applications of a time domain numerical simulation model, capable to predict the dynamic behaviour of a damaged fast ferry, in presence of head or following sea and heeling actions due to the wind. In particular the flooding of a damaged hull and the dynamic behavior of the vessel with water trapped in the garage was investigated.

The first part of the work dealt with some preliminary numerical applications, in order to assess the reliability of the results. The final equilibrium conditions for the intact and damaged ship were compared with the results of a hydrostatic code, showing a good match; the transient stages and ship response in wave were checked too.

From the applications carried out on the ship grounding in presence of longitudinal waves, taking into account dynamic pressure on the damage hole and spilling, it was possible to observe that the water loaded has its maximum and minimum respectively close to wave crest and trough, within a range of almost 9 ton.

The simulation results, regarding the effect of the water trapped on the garage deck with constant wind heeling moment, show that the water presence in the garage compartment leads to higher ship roll and pitch motions.

8. REFERENCES

1. IMO (2009) *SOLAS Consolidated Edition 2009, ISBN: 978-92-801-1505-5,* IMO publications.
2. JANKOWSKI, J., LASKOWSKI, A. (2006) *Capsizing of small vessel due to waves and water trapped on deck. 9th STAB Conference. Rio de Janeiro, Brazil. 2011*
3. CARETTE, N., VAN WALREE, F. (2010) *Calculation method to include water on deck effects. 11th International Ship Stability Workshop, Wageningen, Netherlands. 2010*
4. ACANFORA, M., COPPOLA, T. (2013) *Stability problems arising from fire-fighting measures for ro-ro ship: simulation model and possible actions to improve the drainage system. 15th International Congress of the International Maritime Association of the Mediterranean. La Coruna, Spain. 2013*
5. SANTOS, T., GUEDES SOARES, C. (2006) *Study of the dynamics of a damaged passenger ro-ro ship. 9th STAB Conference. Rio de Janeiro, Brazil. 2011*
6. MAIMUN, A., SETYAWAN, D., ISLAM, M.R., PRIYANTO, A., JASWAR, A. (2011) *Safety of a high speed passenger ferry in damaged condition. Journal of Applied Sciences, ISSN:1812-5654. 2011*
7. RINA (2009) *Rules for the Classification of HSC Craft, Effective from 1 January 2009*
8. LEE, D., HONG, S.Y., LEE, G.-J. (2007) *Theoretical and experimental study on dynamic behavior of a damaged ship in waves. Ocean Engineering 34. 2007*
9. MANDERBACKA, T., MATUSIAK, J., RUPONEN, P. (2011) *Ship Motions Caused by Time-Varying Extra Mass on Board. 12th International Ship Stability Workshop. Alexandria, Virginia. 2011.*
10. MATUSIAK, J. (2013) *Dynamics of a rigid ship. ISBN 978-952-60-5204-5. Aalto University publication series. 2013*
11. SANTOS, T., (2002) *Time domain modelling of the transient asymmetric flooding of Ro-Ro ships. Ocean Engineering, 29(6). 2002.*
12. MIRONIUK, W. (2010) *The influence of the flooding damaged compartment on the metacentric height ship type 888. TransNav-International Journal on Marine Navigation and Safety of Sea Transportation. 2010*
13. ACANFORA, M., DE LUCA, F., COPPOLA, T. (2011) *High speed damage stability criteria: past & present for fast ferry design. 9th HSMV Conference, Napoli, Italy. 2011*
14. FALTINSEN, O. (1990) *Sea loads on ships and offshore structures. Cambridge University Press. 1990*
15. CROSSLAND, P., WILSON, P.A., BRADBURN, J.C. (1993) *The free decay of coupled heave and pitch motions of a model frigate. Transactions of the Royal Institution of Naval Architects 135. 1993.*

