*Developments in Maritime Transportation and Exploitation of Sea Resources –*
*Guedes Soares & López Peña (eds)*
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# Ship stability in wave: A proposal method for dynamic behaviour evaluation

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ABSTRACT: Recent IMO activities are addressed to a renewal process about Intact Stability code. The new generation of stability criteria should be developed in order to be as close as possible to the real physics. The aim of this research work is to develop and validate a tool, intended for displacement vessels, capable to evaluate the ship response to wave actions and its effect on stability. The main advantage of the proposed method is the possibility to estimatethe ship behavior in wave with the effective righting arm variation due to the instantaneous floating condition. The results obtained by the proposed tools are checked by comparison in terms of heave and pitch responses to wave effects, with experimental data. Consideration of effective wave profile on the ship are made, combining the wave pattern with the free surface calculated thought a calm water CFD RANSE multiphase simulation.

## 1 INTRODUCTION

The wave effect on ship stability represents an issue of interest in the recent revision of the intact stability criteria (Francescutto 2007) and (IMO 2009): this work represents a collection of several stability approaches with the development of numerical methods and program tools, in order to evaluate the ship susceptibility to stability failure and capsizing. In particular in the case of pure following sea, a ship could experience the phenomenon of pure loss of stability and parametric rolling (McTaggart and de Kat 2000) and (Blome and Krueger 2003). According to the recent trend the problem is focused mainly on the effects of the sea wave profile on the ship hydrostatics. The aim of this research work is to develop and validate a tool capable to evaluate the ship response to wave actions in terms of instantaneous floating condition (draft and pitch), and to analyze the initial intact stability attitude at each time. The tool, developed in Matlab/Simulink, is characterized by a significant pre-processing and then by a smart and easy simulation toolbox. The pre-processor is capable to calculate the whole hydrostatics, included the metacentric radii, of the ship varying the wave length and amplitude. An appropriate function has been supplied to estimate the Froude-Krylov actions by integrating the wave dynamic pressure on the effective ship wetted surface. Diffraction forces have been neglected. In order to take into account the presence of the ship body moving in the calm sea, the wave pattern generated by the ship has been estimated by CFD calculation. A ship longitudinal dynamic model has been developed to analyze the heave and pitch motions and then a 6DoF has been introduced to examine also the ship transversal response to rolling environmental actions, assuming a pure following sea and constant wind. For both the implemented dynamic models the added mass and the damping coefficients have been estimated by a strip theory computation, neglecting for these hydrodynamic data the effect of the effective wave amplitude. The results obtained by the longitudinal dynamic simulation have been checked and compared with experimental data. The experimental tests have been carried out in the Towing Tank of the Dipartimento di Ingegneria Industriale of University of Naples "Federico II" for a range of frequencies associated to wave length almost of the same size of the ship length. These kinds of wave, in fact, result to be the more critical for initial stability, leading to significant reduction of the metacentric height $GM$ (IMO 2009). In a second part of the work, the sea wave has been combined with the wave pattern generated by the ship model at a velocity $V = 1.367\frac{m}{s}$, and then fed to the developed tool, for a more precise and realistic approach. The wave pattern has been obtained through a calm water CFD RANSE multiphase computation.

## 2 THE DEVELOPED TOOLS

The mathematical model for heave and pitch behavior, is based on common equations for ship longitudinal motions 1. The variable $z$ in the model represents the ship mean immersion from which the heave is deducted, and $\theta$ is the pitch.

$$
\begin{aligned}
&(m+m_{33})\ddot{z}+b_{33}\dot{z}+\rho g\nabla=\Delta+F_{FK3}\\
&(I_y+I_{55})\ddot{\theta}+b_{55}\dot{\theta}+(x_B\cos\theta+z_B\sin\theta)\rho g\nabla=\\
&\quad=(x_G\cos\theta+z_G\sin\theta)\Delta+F_{FK5}
\end{aligned}
\tag{1}
$$

The added mass and inertia $m_{33}$ and $I_{55}$ and the damping coefficient $b_{33}$ and $b_{55}$ have been calculated through strip theory solver. The simplified stiffness approach of $c_{33}=A_{wl}$ and $c_{55}=GM_L$, typical of the strip theory calculation (Fathi and Hoff 2004) is here substituted with a more precise modeling of the buoyancy–weight actions. The pre-processing tool developed in Matlab is composed by several functions that evaluate the whole hydrostatics in wave that figure in eq. 1, as function of the immersion $z$, of the trim $\theta$ and of the relative position of the wave on theship $X_C$. The same parametrization has been assumed in evaluating the excitation Froude-Krylov ($FK$) actions. The $FK$ force eq. 2 has be found through the direct integration of the dynamic pressure of the incident wave on the effective wetted surface (Bhattacharya 1978). In the developed approach, the wave has been frozen on the ship with all the possible relative positions by means of the parameter $X_C$ that in the simulation model is linked to the wave frequency by the eq. 3.

$$F_{FK3}=\int_{S_w}\rho g A e^{-\frac{2\pi}{\lambda}z'}\cos\left(\frac{2\pi}{\lambda}x+X_C\right)dS_w \tag{2}$$

$$X_C=\omega_e t-2\pi N \tag{3}$$

where $z'$ is the initial immersion corrected by the wave profile along the ship hull and $N$ is the number of waves encountered by the ship up to the time $t$. The reference system for this calculation has been assumed to have its origin in the aft perpendicular as shown in Figure 2.

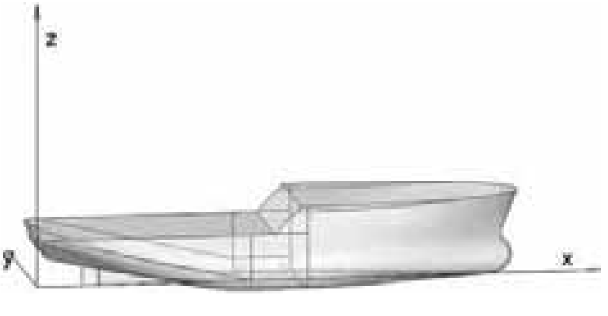

Figure 1. Reference sistem for the hydrostatics calculation.

## 3 VALIDATION ANALYSIS

A first validation of the proposed tools have been performed by comparison with experimental tests carried out in regular wave on a supply vessel model C1102 in head sea. The model refers to a ship whose data are summarized in table 1. The data have been compared in model scale at the velocity of $1.347\frac{m}{s}$ that correspond to a 13 $Kn$ in full scale, with reference to the scale factor of 21. The model has been fixed with a default longitudinal radius of gyration of $25\%L_{wl}$, the test were conducted in self-propulsion condition considering the model self propulsion point to allow the motion of the model in 6 DoF. The tests were performed in 5 different sinusoidal waves, considering waves length significant for the initial stability, according to the physical limits of the model and the instrumentations (see table 2). During the test an active control on propellers speed where used to set the vessel speed to the target value of $1.347\frac{m}{s}$. Heave and Pitch were measured thought laser probes fixed on the model. The Figures 2 and 3 show the comparison between of heave and pitch RAOs evaluated with the proposed tool and the experimental test

Table 1. Main data of the reference ship.

| | |
|---|---|
| Displacement $\Delta(t)$ | 3500 |
| Waterline length $L_{wl}(m)$ | 62.39 |
| Breadth $B(m)$ | 15.53 |
| Draft $T(m)$ | 5.40 |

Table 2. Amplitude and frequency range tested.

| Test number | Amplitude (m) | Frequencies (Hz) |
|---|---|---|
| 1 | 0.030 | 0.80 |
| 2 | 0.030 | 0.72 |
| 3 | 0.034 | 0.68 |
| 4 | 0.037 | 0.65 |
| 5 | 0.042 | 0.58 |

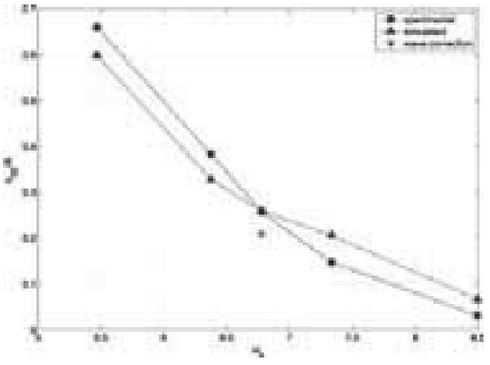

Figure 2. Vertical ship response comparison.

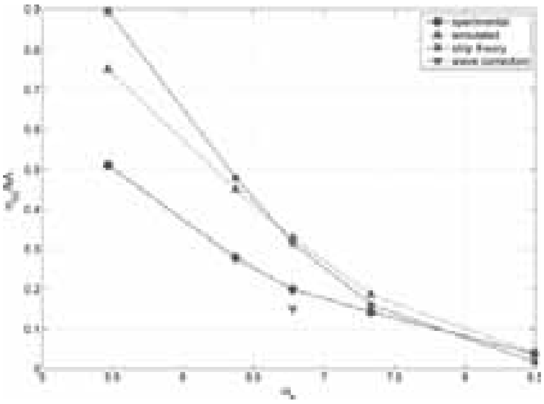

Figure 3. Pitch response comparison.

for the assumed frequencies (table 2). As could be noticed from 2 the tool underestimates slightly the experimental data for frequencies lower than $6.8\frac{rad}{s}$ while the behavior is reversed for the higher frequencies. Regarding Figure 3, the simulation tool tends to overestimate significantly the pitch response, the lower the frequencies taken into consideration, the larger the error. Due to the high differences in the pitch behavior, the strip theory RAO has been introduced in the comparison, showing a good matching with the tool response; both the approaches, in fact, neglect the viscous effects on damping that affect the real phenomenon. The Figures 4 and 5 show, as example, the results of the tool proposed in terms of heave and pith motions in time domain, compared with the experimental

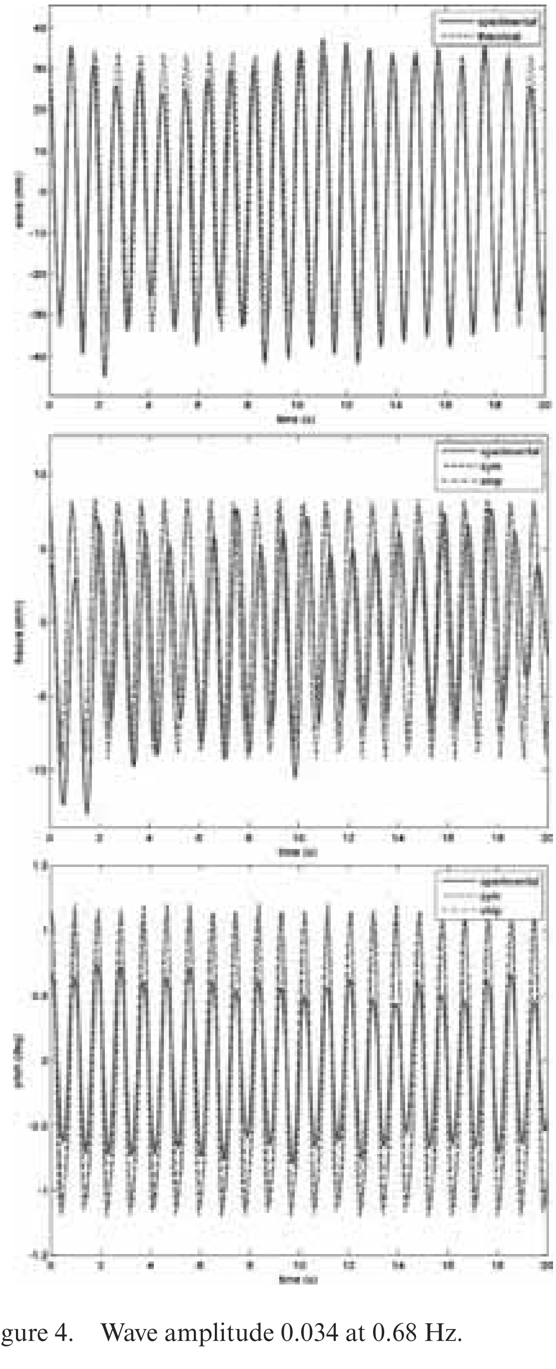

Figure 4. Wave amplitude 0.034 at 0.68 Hz.

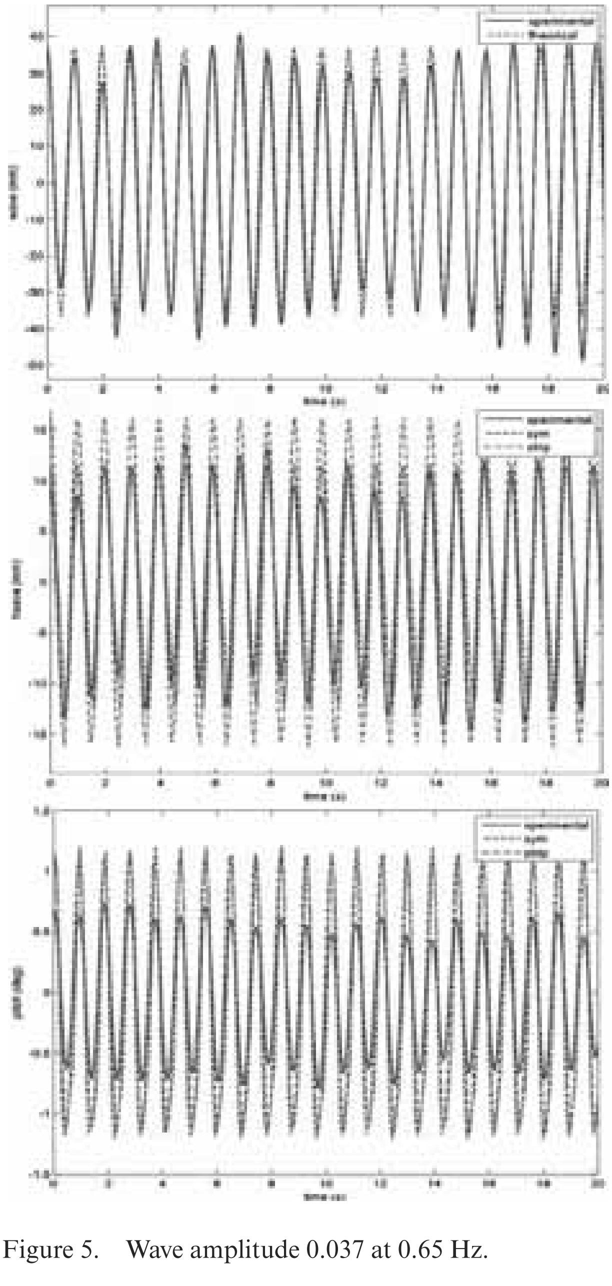

Figure 5. Wave amplitude 0.037 at 0.65 Hz.

data and strip theory for the frequencies of 0.68 *Hz* and 0.65 *Hz*. More tests need to be done to get a clearer picture of the behavior of the tool; in particular it is necessary to analyze a wider range of wavelengths and amplitudes. From the data processed till now the instrument seems to confirm the expectations of validity.

## 4 WAVE PATTERN CALCULATION

A CFD analysis on the model C 1102 have been performed at the speed of $1.347 \frac{m}{s}$ to evaluate the pattern on free surface. Unsteady RANS simulations have been carried out using the finite-volume commercial software Star CCM +. An unstructured trimmed grid of about 1470000 cells has been made (see Figure 6); a prism layer mesh model was used with a core volume mesh to generate orthogonal prismatic cells next to wall boundaries. This layer of cells is necessary to improve the accuracy of the flow solution.

The Volume of Fluid (VOF) multiphase model has been adopted to predict the free-surface flow. Turbulence effects have been taken into account by means of the $\kappa - \varepsilon$ turbulence model (see Figure 7). The CFD calculation has been validate by means of resistance comparison. The numerical data has been confirmed comparing with the experimental data: the results match in a range of 3% in terms of calm water resistance.

### 4.1 *Application of the wave pattern*

The wave pattern correction has been computed from the CFD calculation, assuming calm water and the initial immersion of 0.247 *m* without trim, for the nominal displacement in model scale. The assumption of linearity of the phenomenon has been done. The obtained stationary wave profile has been superimposed to the assumed regular sea wave in recalculating all the hydrostatics and the $FK$ actions in Matlab. For the purpose of the applications, the correction has been carried out only for the frequency of 0.68 *Hz*. In Figures 2 and 3 are reported the RAOs evaluated with the wave pattern approach. The single data for heave and pitch support this kind of method, in taking into account the effect of the pressure field, determined by the ship speed, on the sea wave behavior. However this approach has to be confirmed with a more deep analysis.

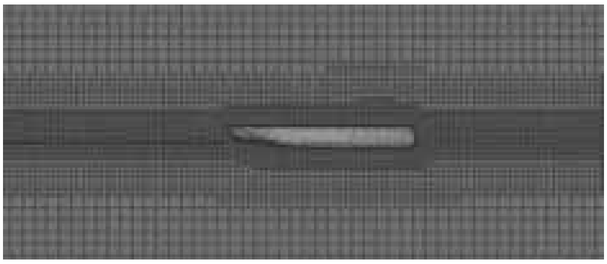

Figure 6. Model grid.

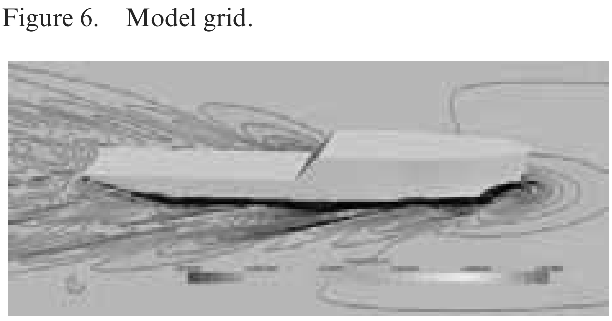

Figure 7. CFD calculation.

## 5 NUMERICAL ROLLING RESPONSE

The 6DoF simulation model for the ship in wave, has been further introduced. The ship rolling response to following waves and constant wind heeling moment, in terms of righting arm variation in time, has been evaluated. The numerical model is based on the eq. 4 developed and applied in the reference work (Acanfora et al., 2012) for calm water.

$$\boldsymbol{M}\begin{bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \boldsymbol{D} + \boldsymbol{F}_d + \boldsymbol{G} + \boldsymbol{B} + \boldsymbol{E} \tag{4}$$

The hydrostatics data implemented refer to the ship model in wave with the wave pattern correction for the interest frequency of 0.68 *Hz*. In the external actions $\mathbf{E}$ figure also the $FK$ vertical force and pitching moment. The wind heeling moment fed to the simulation model has been chosen in order to obtain a mean heeling angle of about 5 *deg*. The Figure 8 shows an example of the output of the implemented model under the assumptions made. The results report the time domain response in terms of draft, $GZ$ and $GM$. The data shows that the stability parameters, calculated through the dynamic simulation, oscillate with relevant amplitude around the mean value. The 6DoF tool could be also applied in assessing the dynamic loss of stability under several environmental actions considering a more realistic approach (Acanfora et al., 2012). This issues will be analyzed more in deep in further applications.

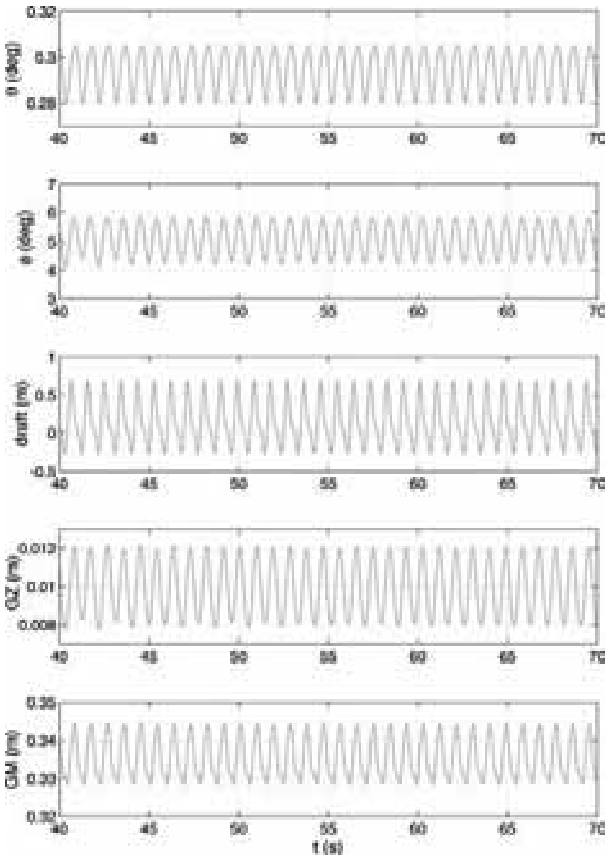

Figure 8. Simulation response in head wave and constant heeling moment.

## 6 GM ESTIMATION IN IRREGULAR SEA

The irregular sea simulation has been carried out considering an ITTC spectrum with $H_{1/3} = 2.5\ m$ and $T = 6\ s$ for a typical ferry operating in the bay of Naples, named $M1$, used in the (Acanfora et al., 2011). This ship (see Figure 9) is characterized by a length of 64.54 *m*, a breadth of 13.40 *m*. For the purpose of the application a displacement of about 500 *t*, with a $VCG$ of 5.06 *m* has been assumed, leading to an initial $GM$ of 3.02 *m*. Five frequencies have been chosen, calculated assuming the following wave length:

$$\lambda = [0.25L, 0.5L, L, 1.5L, 1.75L].$$

For these values, the respective amplitudes have been evaluated from the spectrum (see Figure 10); from these five regular waves, assigning random phases, a the determination in time of the irregular sea, could be obtained. One of the main advantages of the developed tool is the possibility to handle and work with several regular wave data, estimating for each of them the $GM$ variation in time. A function that manage simultaneously the $GM$s estimation for each wave, has been provided. Then the resulting $GM$ variations in time have been summed, assuming the linearity. As could be seen from Figure 11, this kind of approach could allow to evaluate in time domain the vessel behavior, regarding the initial stability, even for irregular sea. This approach will suggest further developments of the tool regarding a statistical post-processing of the data, for assessing ship dynamic stability in all the possible irregular seas, during the vessels life.

Figure 9. View of the M1 ship.

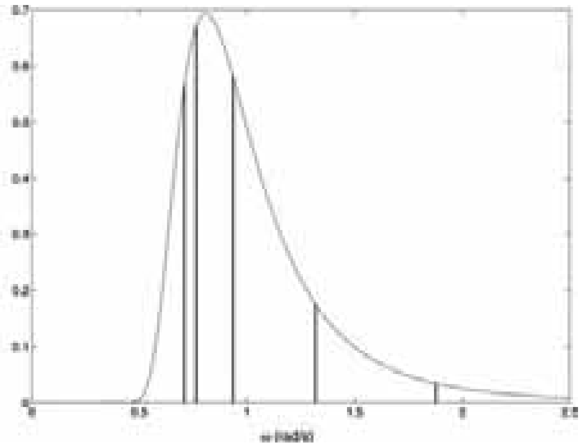

Figure 10. Two parameters ITTC spectrum: $H_{1/3} = 2.5\ m$ and $T = 6\ s$.

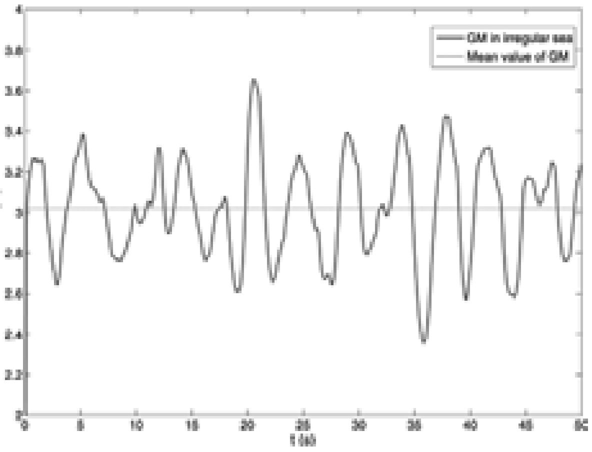

Figure 11. GM variation in irregular sea.

## 7 CONCLUSIONS

In this work a tool for the evaluation of ship stability in wave was developed. The main advantage of the proposed method was the possibility to estimate the ship behavior in wave with the effective $GM$ due to the instantaneous floating condition. A first validation of the tool was provided, by means of comparison with experimental tests. From the data processed till now the results seem to confirm the expectations of validity. However more tests need to be done to get a clearer picture of the behavior of the tool, analyzing a wider range of wavelengths and amplitudes for different conditions. One of the interesting possible applications of this tool, developed in Matlab/Simulink, was the possibility to handle and work with several regular wave data. In this way, assuming the linearity, an irregular sea simulation was carried out summing each $GM$ response in time domain. This approach would allow further developments of the tool regarding a statistical post-processing of the data. The wave pattern generating by the moving ship was calculated trough CFD computation. Assuming linearity, the obtained stationary wave profile was superimposed to the assumed regular sea wave in recalculating all the hydrostatics and the $FK$ actions in Matlab. This approach being not so flexible, was applied only for one frequency but confirms to be more accurate. Anyway further investigations should be addressed to this approach in assessing its validity. Finally the tool, developed for longitudinal motions, was extended to 6DoF to examine the lateral vessel behavior. The righting arm variation in time was estimated, assuming constant wind and regular wave actions. This demonstrates that the 6DoF tool couldbe applied in assessing the dynamic loss of stability under several environmental actions.

## ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the shipping company “Marnavi Spa” for providing the C1102 hull model.

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