Capsizing of Small Vessel Due to Waves and Water Trapped on Deck

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ABSTRACT

The paper presents a study of the influence of water trapped on deck on small vessel survivability in irregular waves. The study is carried out using simulations of vessel motions in waves based on numerical solution of non-linear equations of motion. Theoretical model of the influence of water on car deck, used in analyses of stability safety of Ro-Ro ships, is adopted to calculate the volume of water shipping on the weather deck and flowing out of the deck well. However, computational model of pressure imposed by water on deck is modified and improved.

Simulations of small fishing vessel motions in various irregular waves have been carried out. They proved usefulness of systematic simulations for future development of Goal Based Standards for safety of small vessels. Some general conclusions regarding the application of water-on-deck model, which was developed for Ro-Ro ships, to evaluation of the influence of water-on-deck on small vessel safety are presented.

Keywords: *irregular waves, vessel motion, vessel capsizing, water on deck*

1. INTRODUCTION

The new approach to dynamic stability criteria, which is aimed at development of Goal Based Standards (GBS), is under discussion at the IMO forum. The approach needs a reliable set of simulation programs which would represent all the fundamental features of ship dynamics in severe seas. The study presented in this paper is a first step in the development of an adequate tool for future comprehensive analysis of stability safety in extreme weather conditions.

For the large part, safety initiatives developed by the maritime industry focus on large seagoing vessels such as tankers and bulk carriers. However, figures reported by the IMO itself show that the annual loss of life on world's fishing vessels accounts for the loss of a huge number of human lives every year, and that the safety of small vessels is a real global problem.

One of the important reasons for capsizing of small vessels is water trapped on deck. The influence of water-on-deck on ship motions and on the capability to survive in heavy seas is significant. Correct modelling of hydrodynamic forces imposed by moving water on deck is a very complex and difficult problem, in particular, if continuously changing mass of water on deck is taken into consideration. At present, it is work in progress. The works (Grochowalski, et al, 1998) and (Huang, et al, 1999) present a theoretical model of water on deck with changing mass of water in time. Dynamic effects of sloshing water was modelled in accordance with shallow water waves theory (Huang Z., Ph.D. thesis, 1995). Falzarano et al (Falzarano et al, 2002) applied Glimm method in modelling 3-D flow of shallow water on deck of offshore supply vessel.

Another approach has been presented by Belenky et al (Belenky et al, 2002) which uses a finite-volume solution of water across the deck.

In considering the deck–green water interaction, two different scenarios have to be recognized: water-on-deck and deck-in-water (Grochowalski, 1989 and 1998). In the paper presented, only the first phenomenon is taken into account.

Theoretical models and computer programs enabling simulation of ship motion in irregular waves were earlier developed by the authors (Jankowski & Laskowski, 2005), (Laskowski, 2003) but the problem of vessel motion with water flowing on and off the deck is more complex.

In pursue of robustness of the numerical models under development, a simplified approach used in Ro-Ro ferries damage stability calculations have been applied here, as the first phase of modelling the water-on-deck effects. The main assumption, taken from Vassalos et al (Vassalos, 1997), is that the surface of water on deck is horizontal. This idea was also applied by (Jankowski & Laskowski, 2005), where only the hydrostatic pressure of water on deck and the acceleration of the ship was taken into account in determining the forces acting on the deck.

However, observation of the model experiment (e.g. Grochowalski, 1989) and the numerical calculations carried out showed that the amount of water on deck and the dynamics of its change can have decisive impact on the dynamic stability of small vessels. Therefore, this paper presents a method which takes into account additional pressure acting on the deck, caused by the change of water amount on the deck (formula (5)). This method is based on the evaluation of Newton's momentum relations for a control mass volume over the deck (Buchner, 2002). Integration of the pressure over the wetted part of the deck, taking into account generalised normal vector to the deck, yields additional forces affecting motions of the vessel.

Mathematical model of water sloshing is being developed in parallel, and it will be incorporated into the simulation program in the next phase of development.

Proper evaluation of dynamic stability requires accurate mathematical models enabling determination of the vessel motion in irregular waves. Water flow on and off the deck, which depends on the position of the upper edge of bulwark and on the openings in the bulwark, has to be an essential element in the simulation program. The first version of such a program has been developed and the results of its application are presented in this paper.

A fishing vessel which was regarded as a vessel with good stability has been used in the simulations and the analyses. The results shed some light on the problem of modelling the water-on-deck effects and the application of time-domain simulations to assessment of safety against capsizing of small vessels sailing in irregular waves.

2. EQUATION OF VESSEL MOTION, WITH WATER ON DECK IN IRREGULAR WAVES

The simulation of vessel motions in waves is based on numerical solutions of non-linear equations of motion (non-linear model). The hydrodynamic forces and moments defining the equations are determined in each time step. The accuracy of the simulation depends on the accuracy of calculating the hydrodynamic forces and moments due to waves.

It is assumed that the hydrodynamic forces acting on the vessel can be split into Froude-Krylov forces, diffraction and radiation forces as well as other forces, such as those induced by water on deck, rudder forces and non linear damping.

The Froude-Krylov forces are obtained by integrating the pressure caused by irregular waves undisturbed by the presence of the ship over the actual wetted ship surface

The diffraction forces are determined as a superposition of diffraction forces caused by the harmonic components of the irregular wave. It is assumed that the ship diffracting the waves is in its mean position. This is possible under the assumption that the diffraction phenomenon is described by a linear hydrodynamic problem. The variables of diffraction function are separated into space and time variables with the space factor of the function being the solution of the hydrodynamic problem and the known time factor. Such an approach significantly simplifies calculations because bulky calculations can be performed at the beginning of the simulations and the ready solutions can be applied for determining the diffraction forces during the simulation.

The radiation forces are determined by added masses for infinite frequency and by the so-called memory functions (given in the form of convolution). The memory functions take into account the disturbance of water, caused by the preceding ship motions, affecting the motion of the ship in the time instant in which the simulation is calculated.

The volume of water on deck, varying in time, depends on the difference in heights between the wave surface and the following edges: the upper edge of the bulwark, and the lower edges of openings in the bulwark.

It is assumed that the flow rate of water volume over the bulwark can be calculated as the flow over a weir, whereas the flow through the openings in the bulwark is modelled as a flow through a submerged orifice in a dam. The general formula for the flow rate is:

$$Q = (signH) cb\sqrt{2g}\left(\tfrac{2}{3}|H|^{\frac{3}{2}} + d|H|^{\frac{1}{2}}\right) \tag{1}$$

where c is the correction coefficient for non-stationary flow, established experimentally, b is the width of the orifice or the fragment of bulwark above which the deck is flooded, $H=\zeta - h$ is the vertical distance between the wave profile and the free surface on the deck at a point considered (positive if the wave exceeds the water level on the deck), d is the depth of water at the orifice or the instantaneous elevation of wave profile above the deck edge at the orifice. Formula (1) assumes various forms depending on relative water levels inside and outside the deck well and on the position of the opening in the bulwark (Pawłowski,2004). The formula (1) is applied separately for the upper edge of bulwark and the openings in the bulwark.

The position of water trapped on deck is determined by the horizontal plane and the actual position of the vessel deck in the given time instant.

The dynamics of water caused by the motion of water particles in relation to the deck is neglected. The forces and moments caused by water-on-deck are obtained by integrating the hydrostatic pressure determined by water horizontal plane above the deck in the vessel's actual position, vessel's acceleration and by changing heights of the horizontal plane above the deck.

The equations of ship motion in irregular waves are written in the non-inertial reference system. The system Q is fixed to the ship in the centre of its mass and the equations of ship motion assume the following form (Jankowski, 2006):

$$\begin{aligned} & m[\dot{\mathbf{V}}_Q(t) + \mathbf{\Omega}(t)\times\mathbf{V}_Q(t)] = \mathbf{F}_W(t) + \\ & + \mathbf{F}_D(t) + \mathbf{F}_R(t) + \mathbf{F}_T(t) + \mathbf{F}_A(t) + mD^{-1}\,\mathbf{G}, \\ & \dot{\mathbf{L}}(t) + \mathbf{\Omega}(t)\times\mathbf{L}(t) = \mathbf{M}_{QW}(t) + \\ & + \mathbf{M}_{QD}(t) + \mathbf{M}_{QR}(t) + \mathbf{M}_{QT}(t) + \mathbf{M}_{QA}(t), \end{aligned} \tag{2}$$

$$\dot{\mathbf{R}}_{UQ}(t) = \mathbf{V}_Q(t) - \mathbf{\Omega}(t) \times \mathbf{R}_{UQ}(t),$$
$$(\dot{\varphi}(t), \dot{\theta}(t), \dot{\psi}(t))^T = D_\Omega^{-1} \mathbf{\Omega}(t)$$

where m is the mass of the vessel, $\mathbf{V}_Q = (V_{Q1}, V_{Q2}, V_{Q3})$ is the velocity of the mass centre, $\mathbf{\Omega} = (\omega_1, \omega_2, \omega_3)$ is angular velocity, $\mathbf{L} = (l_{Q1}, l_{Q2}, l_{Q3})$ is the angular momentum, $\mathbf{R}_{UQ} = (x_{UQ1}, x_{UQ2}, x_{UQ3})$ is the position vector of the ship mass centre in relation to the inertial system U, moving with a constant speed equal to the average speed of the vessel, (φ, θ, ψ) are Euler's angles representing roll, pitch, yaw, $\mathbf{F}_W$, $\mathbf{F}_D$ and $\mathbf{F}_R$ are Froude–Krylov, diffraction and radiation forces, respectively, $\mathbf{G} = (0, 0, -g)$, $\mathbf{M}_{QW}$, $\mathbf{M}_{QD}$, $\mathbf{M}_{QR}$ are their moments in relation to the mass centre, D is the rotation matrix, and D_Ω is the matrix which transforms Euler components of rotational velocity $(\dot{\varphi}, \dot{\theta}, \dot{\psi})$ into $\mathbf{\Omega}$. The additional forces and moments such as damping forces or those generated by the rudder are denoted by $\mathbf{F}_A$ and $\mathbf{M}_{QA}$.

The ways of solving 3D hydrodynamic problems and determining forces appearing in the equation of motion are presented in (Jankowski, 2006).

The forces $\mathbf{F}_T$, and moments $\mathbf{M}_{QT}$ caused by water on deck, are calculated according to the following formula:

$$F_i = -\rho \int_{Sd} p \cdot n_i ds, \quad i = 1,2,..,6 \tag{3}$$

where S_d is the wetted surface of the deck, n_1, n_2, n_3 are components of the normal vector in the considered deck point:

$$\begin{aligned} n_4 &= x_{QP2} n_3 - x_{QP3} n_2, \\ n_5 &= x_{QP3} n_1 - x_{QP1} n_3, \\ n_6 &= x_{QP1} n_2 - x_{QP2} n_1 \end{aligned} \tag{4}$$

where n_4, n_5, n_6 are the components of $\mathbf{R}_{QP} \times \mathbf{n}$ and $\mathbf{R}_{QP} = (x_{QP1}, x_{QP2}, x_{QP3})$ is the position vector of deck point P in non inertial system Q (the components of the normal vector are determined in the reference system fixed to the vessel in its centre of mass). The pressure in this point is equal to:

$$p = \rho \frac{dh}{dt} w + \rho (g + a_v) h \tag{5}$$

where

$$\begin{aligned} w &= d_{31} V_{P1} + d_{32} V_{P2} + d_{33} V_{P3}, \\ a_V &= d_{31} A_{P1} + d_{32} A_{P2} + d_{33} A_{P3}, \\ \mathbf{V}_P &= \mathbf{V}_Q + \mathbf{\Omega} \times \mathbf{R}_{QP}, \\ \mathbf{A}_P &\approx \dot{\mathbf{V}}_Q + \dot{\mathbf{\Omega}} \times \mathbf{R}_{QP} \end{aligned} \tag{6}$$

d_{3i}, $i = 1,2,3$, are components of the matrix D and h is the vertical distance of the horizontal plane from the point of the deck in the inertial coordinate system U. Velocity w and acceleration a_v are also determined in the system U.

This formula has been derived basing on the evaluation of Newton's momentum relation for a control volume on deck in the following way (Buchner, 2002):

$$\Delta F = \frac{d(\Delta m w)}{dt} = \frac{d(\Delta m)}{dt} w + \frac{dw}{dt} \Delta m \tag{7}$$

where ΔF is the force acting on the area ΔA of the deck containing the point P considered. The mass in the control volume is equal to: $\Delta m = \rho h \Delta A$. Substituting this to (7), dividing by ΔA and taking into account gravitational acceleration g, results in formula (5).

The non-linear equations of motion (2) are solved numerically (Hamming procedure is applied) according to the method presented in (Ralston, 1975).

3. SIMULATION OF FISHING VESSEL MOTION IN IRREGULAR WAVES

The program based on equations presented above and on the numerical methods applied enables to perform simulations of vessel motion with water on deck in irregular waves. The example of simulated history of water flowing on and off the deck and respective influence on vessel motion is presented in Fig.1 and Fig.2. The wave parameters are: significant wave height $H_S = 5.0$ m, wave average zero-up crossing period T_Z=7 s and the angle between vessel forward velocity and wave direction $\beta = 150°$. The assumed vertical position of the centre of mass $KG = 2.24$ m from base line (keel).

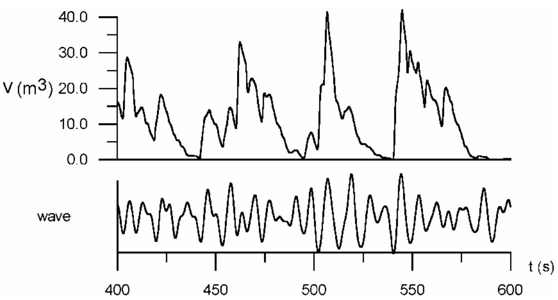

Figure 1 Time history of volume of water trapped on deck and wave surface elevation.

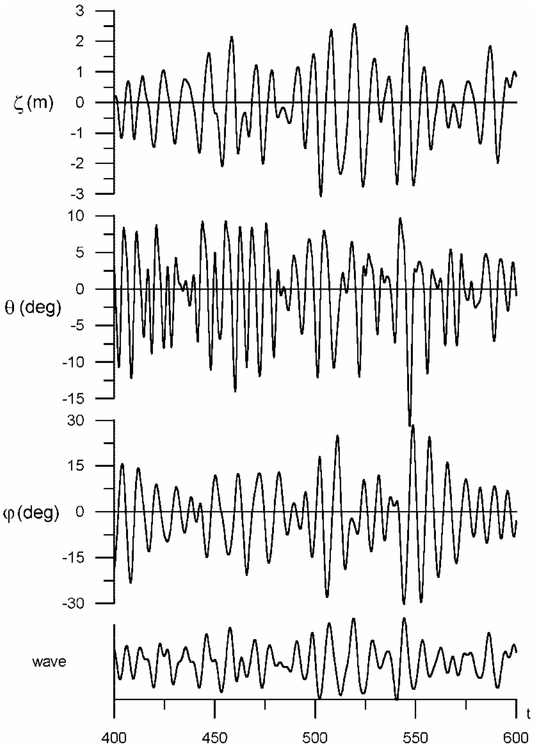

Figure 2. Time history of heave, pitch, roll and wave surface elevation (corresponding to Fig.1)

The freeze frames of vessel motion in irregular waves and capsizing of the vessel are presented in Fig. 3 and Fig. 4.

Figure 3 Freeze frame of substantial vessel motion in irregular waves

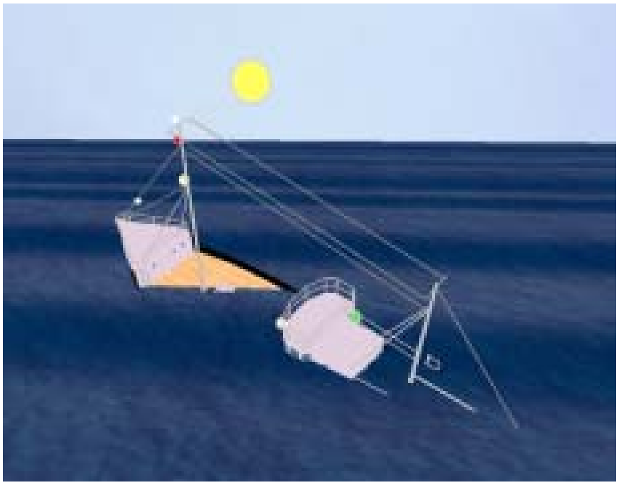

Figure 4 Freeze frame of vessel capsizing

4. ANALYSIS OF FISHING VESSEL DYNAMIC STABILITY

A fishing vessel, which in practice showed good seakeeping ability was used to analyse its dynamic stability. The main parameters of the vessel are: length $L = 24.60$ m, breadth $B = 6.57$ m, draught $T = 2.64$ m and the maximum vertical position of the centre of mass from the vessel base line assumed by the designer is 2.64 m. The vessel speed in each simulation case was 6 knots.

The simulations of the vessel's motion have been carried out in irregular waves, determined by the significant wave height H_S and average zero up crossing period T_Z, for various vessel courses β in relation to waves and for two positions of the vessel centre of mass. The wave parameters used correspond to the wave conditions developed in Baltic and North Sea by wind force of 8 to 11 degrees in Beaufort scale. These parameters are given in Table 1. The Table presents the extreme values of:

- - displacement Z_{re} of the deck at side in midship in relation to the wave surface,
- - heel angles φ_e,

which can occur in three hours time with the probability of exceedance ε = 0.01. These probabilistic parameters are calculated according to the formula (Ochi, 1998):

$$y_e = \sqrt{2\ln\left(\frac{3600t}{0.01}\frac{n}{t_s}\right)m_{oy}} \qquad (8)$$

where y_e assumes value Z_r or φ depending on the quantity considered, m_{oy} is the variance of Z_r or φ respectively, n is the number of heeling periods in simulation or number of times the wave surface exceeds the deck surface at side in midship, t_s is the time of simulation and t is the time in which the vessel is expected to sail in irregular waves. Time t is taken as equal to three hours. The parameters: m_{oy} and n have been calculated simulating vessel motion in irregular waves in t_s = 1000s.

The third value presented in Table 1 for each H_s, T_z, and β, is the amount of water V_m trapped on deck, which probability of exceedance is equal to p. Value of p is equal to $1/n_o$, where n_o is the number of water occurrences on the deck in three hours. To determine the value V_m for each simulation the Weibull distribution

$$F(V) = 1 - exp\left[-\left(\frac{V}{\eta}\right)^{\xi}\right] \qquad (9)$$

has been fit to the relative frequencies of water volume maxima occurring during the simulation (Fig.1). The scale parameter η and the shape parameter ξ are determined with the use of the least squares method. Fig.5 shows the Weibull probability density function fit to the grouped relative frequency of occurrence of water volume maxima.

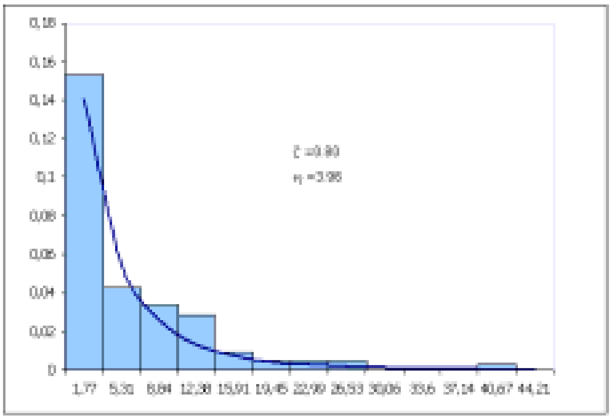

Fig. 5. Weibull probability density function fit to the grouped relative frequency of occurrence of water volume maxima.

Quite steep waves have been chosen. The steepness parameters:

$$s = \frac{H_S}{1.56T_z^2} \qquad (10)$$

belongs to the interval (0.035,0.071).

The shaded area in the Tables denotes that the vessel capsized in these waves.

Table 1. Probabilistic parameters: Z_{re} [m], φ_e [°]/ V_m [m^3].

BALTIC SEA									
KG=2.24 m									
(H_s / T_z)	(2/6)			(3/6)			(4/6)		
β[°]	Z_{re}	φ_e	$\lvert V_m\rvert$	Z_{re}	φ_e	$\lvert V_m\rvert$	Z_{re}	φ_e	$\lvert V_m\rvert$
0	0.03	2.2	0.3	0.57	2.8	3.5	0.92	3.6	5.9
30	0.10	8	0	0.18	13.1	1.5	0.51	17.8	4.5
60	0.14	32	0.5	0.54	48	3.5			
90	1.3	48.5	4.7	2.25	68.4	10.8			
120	0.99	35.6	5.1	2.04	57.5	11.9			
150	0.52	21.7	4.7	1.28	33.8	13.4	2.2	45.3	39.6
180	0.23	8.4	5.4	0.86	11.8	20	1.6	18.5	36.8

KG=3.04 m									
(H_s/T_z)	(2/6)			(3/6)			(4/6)		
$\beta[°]$	Z_{re}	φ_e	$\lvert V_m \rvert$	Z_{re}	φ_e	$\lvert V_m \rvert$	Z_{re}	φ_e	$\lvert V_m \rvert$
0	0.03	3.6	0	0.6	5.7	3	1.14	10.6	9.6
30	0.13	17.5	0.2	0.23	25.6	9.6	0.69	33.3	9.5
60	0.2	21.1	4.7	0.71	30.9	7.8			
90	0.42	18.7	2.8	1.21	26.8	11	2.24	41.7	22.4
120	0.46	14	5.1	1.37	26.2	11.2			
150	0.4	10.4	6.4						
180	0.27	5.2	3.8	1.03	16.7	15.4			
NORTH SEA									
KG=2.24 m									
(H_s/T_z)	(5/7)			(6/8)			(7/9)		
$\beta[°]$	Z_{re}	φ_e	$\lvert V_m \rvert$	Z_{re}	φ_e	$\lvert V_m \rvert$	Z_{re}	φ_e	$\lvert V_m \rvert$
0	0.97	4.2	7	0.84	4.4	3.5	0.99	4.5	5.3
30	0.39	17.5	4.6	0.5	19.2	9	0.5	18.6	5.3
60	1.06	62.5	25	1.14	59.4	10.2	0.98	56.4	11
90									
120									
150				2.31	49.6	92.6	2.12	45.5	33.6
180	1.72	20.4	46.1	1.75	21.1	46.4	1.61	16.8	44.4

It can be seen that the dynamic behaviour of the analyzed vessel in irregular waves depends on the amount of water on deck, which in turn depends on the displacement Z_r of the deck in relation to the wave surface. The relative motion depends on the vessel design (vessel shape, position of its centre of mass), wave steepness and the vessel course in relation to waves. The amount of water trapped on deck (Fig.1 and 4) depends additionally on the possibility of the water getting on deck (low bulwark, openings in the bulwark) and on the means facilitating easy water outflow off the deck.

The results presented in Table 1 suggest that bow waves are more conducive to water shipping on deck than quartering/following waves and lead to capsizing more often. This is a contradiction to real facts. Apparently, the simplified method of computation of the volume of green water shipping on deck does not represent the real amount of water sufficiently well. The mass of water depends not only on the relative water level but also on the horizontal component of the relative velocity of water flow, which is strongly affected by the form of the hull and the bulwark. After exceeding certain vertical velocity threshold in relation to the wave surface, the vessel is passing its momentum to surrounding water causing rejection of the water by the vessel. Therefore, the influence of the ship entrance into water on the water flow in and out off the deck should be investigated in the next step.This is not modelled in the Ro-Ro approach. Also, the assumption on the horizontal plane of water surface on the weather deck seems not to be right. It has to be improved.

5. CONCLUSIONS

The first version of a time-domain program for simulation of full range ship motions in irregular waves with the influence of water-on-deck has been developed. The objective was to provide a numerical tool for systematic studies of small vessels stability safety in extreme weather conditions.

The fishing vessel, which in practice proved to have a good dynamic stability, was selected for systematic simulations of the vessel motions in irregular waves, moving along different courses in relation to waves. The analysis showed that the amount of water trapped on deck may be a decisive factor in vessel safety.

The results of the computations prove that the use of systematic simulations leads to comprehensive information on ship dynamic behaviour and can be an efficient tool in development of stability safety standards. However, the quality of the information gained depends on the correctness of the mathematical model representing ship dynamics with all the additional phenomena affecting its behaviour.

Thorough validation of the simulation software against good, reliable model tests is imperative.

The simplified model of water-on-deck used in Ro-Ro ships damage considerations, based on vertical distance between water surface and bulwark edge is too simplistic and does not model dynamic effects of water on the weather deck sufficiently well. It does not represent correctly the amount of water shipping on the weather deck. More sophisticated model which includes horizontal relative velocity of water in diffracted waves has to be developed.

The assumption that water on deck is always a horizontal plane is also too simplified. It may work well in case of flooded compartments of Ro-Ro ferries, where the ship behaviour seems to be quasi-static. In case of water on weather deck of a small vessel, ship motions are large and the water moves dynamically on the deck. This requires different approach. The sloshing effects must be included to describe the motion of water trapped on the deck of small vessel. The sloshing problem has been already solved, appropriate program developed and it will be included in the next version of the program.

Despite the fore mentioned deficiencies, the modification of pressure imposed on deck due to variations of mass of trapped water seems to be an improvement in comparison with the original model.

The future simulation program developed for the purpose of formulation of performance-based stability safety criteria have to reflect full dynamics of ship motions in extreme weather conditions. It has to account for all physical phenomena which affect the motion, including deck-in-water effects. On the other hand, it has to be relatively simple, robust and reliable.

At the moment, on the basis of the simulations carried out, it can be concluded that appropriate criteria on:freeboard height and on the longitudinal curvature (sheer) of the vessel deck along its side;cross section curvature of the deck;means reducing water inflow on deck and facilitating water outflow off deck should be developed.

6. ACKNOWLEDGMENTS

The authors would like to thank Prof. M. Pawłowski for discussing some results of the paper.

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