Capsizing of small vessel due to waves and water trapped on deck

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ABSTRACT

The paper presents the phenomenon of small vessel capsizing due to irregular waves and water trapped on deck. The phenomenon is identified by simulating vessel motions in waves based on numerical solution of non-linear equations of motion.

The volume of water on deck, varying in time and affecting ship motions, depends on the distance between the wave surface and the upper edge of the bulwark or the lower edges of openings in the bulwark.

This paper is a continuation of earlier works on simulation of fishing vessel motions in irregular waves leading to its capsizing (Jankowski & Laskowski, 2005a). Some general conclusions regarding fishing vessel safety have been drawn.

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

1. INTRODUCTION

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. Theoretical models and computer programs enabling simulation of ship motion in irregular waves were earlier developed by the authors (Jankowski & Laskowski, 2004), (Jankowski & Laskowski, 2005b), (Laskowski, 2002) but the problem of vessel motion with water flowing on and off the deck is more complex.

Simplified models regarding forces induced by water on deck have been applied. 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, 2005a), 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.

This paper presents results based on a more sophisticated method regarding the determination of the pressure acting on the deck (Buchner, 2002), based on the evaluation of Newton's momentum relations for a control mass volume over the deck. 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.

A fishing vessel, which was regarded as having good stability, has been used in simulations and the analyses. The results showed essential features influencing safety of fishing 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 over the actual wetted ship surface the pressure caused by irregular waves undisturbed by the presence of the ship.

The diffraction forces (caused by the presence of the ship diffracting the waves) 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,

- the lower edges of openings in the bulwark.

The inflow and outflow of water on the deck are determined by the hydraulics formulae of (Pawłowski, 2002) and depend on the dimensions of holes in the bulwark. When the wave profile exceeds the upper bulwark edge, the amount of inflowing water on deck is determined by the dimensions of the cross section of the wave by the extended bulwark surface.

The amount of water trapped on deck and its position is determined by the horizontal plane and the actual position of the vessel deck in the given time instant. If the plane is higher than the lowest point of the bulwark above the wave surface than the horizontal plane is taken on the level of this bulwark point.

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 in time 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):

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

where m is the mass of the vessel, $\mathbf{V}_Q = (\mathrm{V}_{Q1}, \mathrm{V}_{Q2}, \mathrm{V}_{Q3})$ is the velocity of the mass centre, $\mathbf{\Omega} = (\omega_1, \omega_2, \omega_3)$ is angular velocity, $\mathbf{L} = (\mathrm{l}_{Q1}, \mathrm{l}_{Q2}, \mathrm{l}_{Q3})$ is the moment of momentum, $\mathbf{R}_{UQ} = (\mathrm{x}_{UQ1}, \mathrm{x}_{UQ2}, \mathrm{x}_{UQ3})$ 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, $\mathbf{F}_W$, $\mathbf{F}_D$ 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:

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

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:

$$
\begin{aligned}
n_4 &= x_{QP2}n_3 - x_{QP3}n_2, \\
n_5 &= x_{QP3}n_1 - x_{QP1}n_3, \\
n_6 &= x_{QP1}n_2 - x_{QP2}n_1
\end{aligned}
\qquad (3)
$$

and $\mathbf{R}_{QP} = (\mathrm{x}_{QP1}, \mathrm{x}_{QP2}, \mathrm{x}_{QP3})$ 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:

$$
p = \rho \frac{dh}{dt} w + \rho(g + a_v)h \qquad (4)
$$

where

$$
\begin{aligned}
& w = d_{31}V_{P1} + d_{32}V_{P2} + d_{33}V_{P3}, \\
& a_V = d_{31}A_{P1} + d_{32}A_{P2} + d_{33}A_{P3}, \\
& \mathbf{V}_P = \mathbf{V}_Q + \mathbf{\Omega}\times\mathbf{R}_{QP}, \\
& \mathbf{A}_P \approx \dot{\mathbf{V}}_Q + \dot{\mathbf{\Omega}}\times\mathbf{R}_{QP}
\end{aligned}
\qquad (5)
$$

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):

$$
\Delta F = \frac{d(\Delta m w)}{dt} = \frac{d(\Delta m)}{dt} w + \frac{dw}{dt} \Delta m \qquad (6)
$$

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 (6), dividing by ΔA and taking into account gravitational acceleration g, results in formula (4).

The non-linear equations of motion (1) 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 developed 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 simulated history of water flowing on and off 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 β = 180º. The assumed vertical position of the centre of mass KQ = 2.24 m from base line (keel).

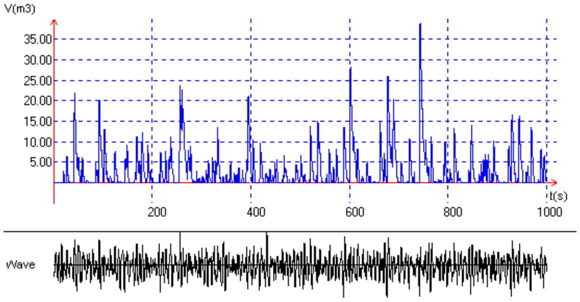

Fig. 1. Time history of volume of water trapped on deck and wave surface elevation.

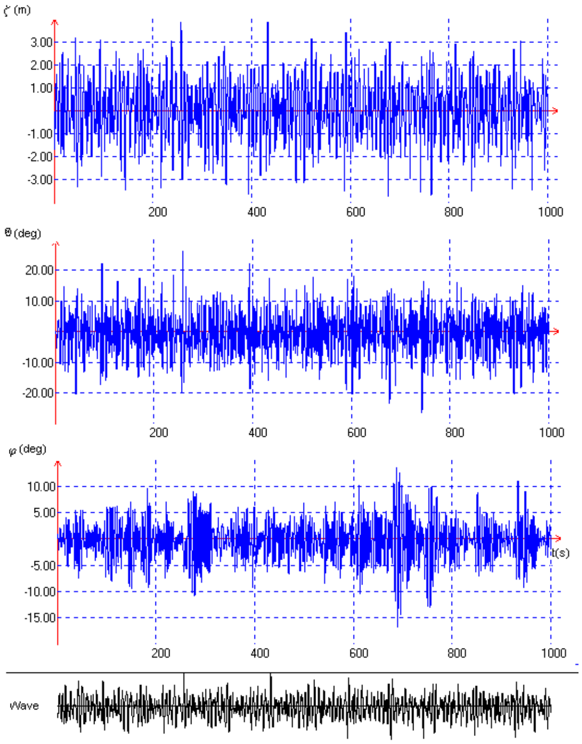

Fig. 2. Time history of heave, pitch, roll and wave surface elevation (corresponding to Fig.1)

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

Fig. 3. Freeze frame of substantial vessel motion in irregular waves

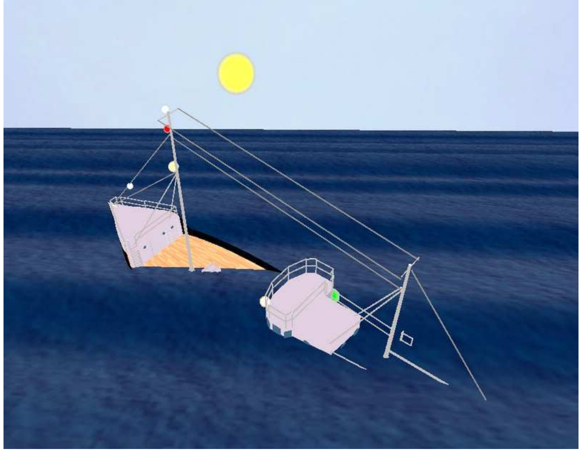

Fig. 4. Freeze frame of vessel capsizing

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

$$y_e = \sqrt{2ln(\frac{3600t}{0.01}\frac{n}{t_s})m_{oy}} \tag{7}$$

where y_e assumes value Z_r or φ respectively, 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

$$F(V) = 1 - exp\left[-\left(\frac{V}{\eta}\right)^{\xi}\right] \tag{8}$$

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 densities of water volume maxima occurrence.

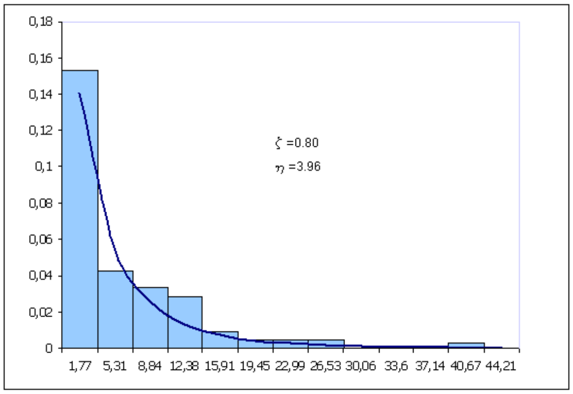

Fig. 5. Weibull probability density function fit to grouped relative frequency densities of water value maxima occurring on the deck

Quite steep waves have been chosen. The steepness parameters:

$$s = \frac{H_S}{1.56 T_z^2} \tag{9}$$

where s of the chosen waves belongs to the interval (0.035,0.071).

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

BALTIC SEA

KQ=2.24

(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

KQ=3.04

(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	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

KQ=2.24

(H_S,T_Z)	(5.7)			(6.8)			(7.9)		
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	0.97	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

Table 1. Probabilistic parameters: Z_{re} / φ_e / V_m

It can be seen from the Tables that the dynamic stability of the analyzed vessel motion 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) 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 deck.

Following seas generate smaller relative motions than head seas, which result in a smaller quantity of water inflowing on deck. It is not clear whether sailing in following seas is safer as such phenomenon as broaching has not been analyzed.

The higher position of vessel centre of mass reduces the relative motions only in beam seas (softer vessel motion) for irregular waves taken in the simulations, and increases in other cases, which results in reduction of safety.

5. CONCLUSIONS

The fishing vessel, which in practice proved to have good dynamic stability, was chosen to perform simulation of the vessel motion in irregular waves, moving along different courses in relation to waves. The analysis showed that the amount of water trapped on deck is decisive for vessel safety.

To conclude, for improvement of fishing vessel safety further analysis of vessel motion simulation, taking into account different vessels representing their class, different loading conditions and a wider range of irregular waves and vessel courses, need to be and are to be carried out. These analyses will be done in the next step.

However, basing on the simulations carried out it can be concluded that appropriate criteria on:

- freeboard 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. Good seamanship practice of the crew is also important.

Examples presented show that in some cases following seas are less dangerous than head seas as they reduce the relative motions.

To improve the safety of existing vessels that are not intended for any conversion work, the areas of their operation and the sea state should be appropriately restricted to satisfy the safety criteria mentioned. Further studies, like these presented here, will make it possible to determine the safe sea states.

6. ACKNOWLEDGMENTS

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