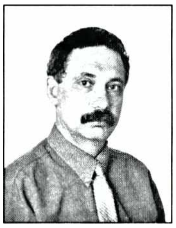

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Numerical modelling of damaged ro-ro ship's motions in waves

SUMMARY

In the paper presented is an algorithm for numerical modelling the damaged ship's behaviour in waves.On this basis the computer software called KOŁYSANIA which makes it possible to simulate ship's motions in irregular waves, was developed. The program can serve as a fully functional, user's friendly instrument for carrying out design projects and elaborating improved safety standards for ships in service.

1. INTRODUCTION

In the 1950s the ferry traffic making it possible to ship simultaneously passengers and vehicles on short sea routes, became very important. Initially, as regards the requirements for safety at sea, the ferries have been considered identically as the passenger ships. The intensive traffic of the ro-ro passenger ferries has resulted in a large number of sea accidents leading to numerous casualties. It made it necessary to investigate causes of the accidents more comprehensively [3].

Till the beginning of the 1990s the only practical method of predicting the ferry's behaviour in rough weather conditions was to test it in a model basin. However it turned out that such tests, when applied to a ship damaged due to collision, have been physically ill-conditioned, i.e. very sensitive to all kind inaccuracies. For instance, in model basin it is very hard to obtain a wave of assumed parameters. Hence the wave spectrum generated for model testing may significantly differ from that assumed. The model drifts during such tests. In order to ensure a sufficiently long duration time for the tests, the model must be kept with elastic strings. It makes ship's rolling distorted and, in consequence of the mutual coupling of particular ship motions, all the motions changed. Next, it affects mass of water entering the car deck, as the water shipping results from the motions.

As a result of the above mentioned factors a strong need arises to develop alternative methods for predicting the damaged ship's seakeeping qualities. For this purpose, it should appear helpful to elaborate suitable mathematical models, and - on their basis – computer programs which could aid in simulating damaged ship's motions in waves.

Till the end of the 1980s the developments in the area of the elaboration of mathematical models for predicting the damaged ship's seakeeping qualities, were not large. The potential possibilities residing in the computer numerical simulations free of the ill conditions associated with the testing of physical models, were appreciated as late as in the middle of the 1990s.

In the worldwide literature on the subject in question one can find some publications showing the great interest paid to developing the numerical hydrodynamics in such a way as to make it possible to analyze the damaged ship's motions in waves. In this area especially important are the results obtained by Vassalos [12]. Also, at the University of Athens some investigations aimed at the developing of the numerical algorithms are carried out by Papanikolaou and his team. A nonlinear mathematical model based on the constant displacement method, and a relevant computer program, next verified by means of model tests in a basin, has been elaborated. In the presented comparative analysis it was stated that the numerical simulation results satisfactorily complied with the model tesing results [8].

In Poland the first attempts to elaborate a theoretical model have been undertaken by Ship Design & Research Centre in Gdańsk. In 1997 an algorithm for computer calculations of the wave-and-wind-induced beam motions of a damaged passenger ro-ro ferry, was developed. In 1999 on this basis elaborated was the TISFLOD computer software which made it possible to realize simulations of ship's behaviour in irregular waves [6]. Also, series of experiments were performed in a model basin, whose results were used to verify the calculation results obtained from the TISFLOD. Their results have been proved to be promising.

2. DESCRIPTION OF SHIP MOTION

All motion equations were consistently described in the movable ship-fixed reference system because another approach involved unnecessary mathematical limitations [4].

2.1 General form of ship translational motion equations

The initial equations of the ship translational motions in the movable reference system, resulting from 2nd Newtonian principle of dynamics, can be described as follows [10] :

$$m(\dot{V}+\Omega\times V)=F$$
$$\dot{R}+\Omega\times R=V \qquad (2.1)$$

where :
- F – external force exerted on a ship
- m – mass of a ship
- V – oscillation velocity of the ship's centre of gravity, G, around its average position
- R – vector of translations of the ship's centre of gravity, G, around its average position
- Ω – angular velocity vector.

The expression within brackets is the acceleration of the ship's centre of gravity, a_G. The components $\Omega \times V$ and $\Omega \times R$ express that the derivatives of the vectors of the velocity V and of the linear translations R are determined in the movable reference system associated with the ship.

The two above given vectorial equations are equivalent to the following six scalar equations :

$$m(\dot{V}_x+\Omega_y V_z-\Omega_z V_y)=F_x$$
$$m(\dot{V}_y+\Omega_z V_x-\Omega_x V_z)=F_y \qquad (2.2)$$
$$m(\dot{V}_z+\Omega_x V_y-\Omega_y V_x)=F_z$$

$$\dot{R}_x=V_x-\Omega_y\dot{R}_z+\Omega_z\dot{R}_y$$
$$\dot{R}_y=V_y-\Omega_z\dot{R}_x+\Omega_x\dot{R}_z \qquad (2.3)$$
$$\dot{R}_z=V_z-\Omega_x\dot{R}_y+\Omega_y\dot{R}_x$$

where :
- F_x, F_y, F_z – components of resultant external force acting on a ship
- R_x, R_y, R_z – components of the vector, R, of translation of the ship's gravity centre.

2.2 General form of ship rotational motion equations

The initial equations of the ship rotational motion in the movable reference system, resulting from the 2nd Newtonian principle of dynamics, can be described as follows [9] :

$$\frac{d'K}{dt}+\Omega\times K+V_p\times P=M \qquad (2.4)$$

where :
- P – ship's momentum
- K – ship's angular momentum
- V_p – pole velocity
- M – moment of external force acting on a ship.

On the assumption that the pole is placed in the ship's centre of gravity, the centrifugal moments are equal to zero, as well as that $I_y \approx I_z = I_L$, the equation (2.4) can be expressed in the following form:

$$I_x\dot{\Omega}_x=M_x$$
$$I_L\dot{\Omega}_y+(I_x-I_L)\Omega_z\Omega_x=M_y \qquad (2.5)$$
$$I_L\dot{\Omega}_z+(I_L-I_x)\Omega_x\Omega_y=M_z$$

where :
- M_x, M_y, M_z – components of external force moment acting on a ship, determined in respect to ship's centre of gravity
- I_x, I_L – ship's moments of inertia
- $\Omega_x, \Omega_y, \Omega_z$ – components of angular velocity vector.

In order to make the equations (2.5) complete they must be supplemented, like the dynamic translational motion equations, by the kinematic relationships between the angular velocity vector Ω and the derivatives of the Euler angles $\dot{\alpha}(\dot{\varphi}, \dot{\theta}, \dot{\psi})$. The relationships are given by the expressions [9] :

$$\dot{\varphi}=\Omega_x+\theta\sin\varphi\,\Omega_y+\theta\cos\varphi\,\Omega_z$$
$$\dot{\theta}=\cos\varphi\,\Omega_y-\sin\varphi\,\Omega_z \qquad (2.6)$$
$$\dot{\psi}=\sin\varphi\,\Omega_y+\cos\varphi\,\Omega_z$$

3. FORCES APPEARING IN SHIP MOTION EQUATIONS

The basic difficulty in solving the ship motion equations is the determination of external forces and moments acting on a ship in heavy seas. An exact determination of the forces, e.g. by using the method of integral equations or the method of finite elements [1] is too time-consuming for a computer program realizing real-time calculations when it is necessary to determine them in each time-step. Therefore one should base on such hypotheses and models which are able to provide us with the results sufficiently exact to be applicable in practice, but demanding a smaller outlay of calculations, hence making their realization faster. It was assumed that a satisfactory simulation of ship motions can be obtained in the frame of the hypothesis of two dimensional flow around ship's hull. Aditionally, it was assumed that the hydrodynamical forces acting on ship's hull can be split into three independent parts, namely :

- Froude – Krilov's forces
- radiation forces
- diffraction forces.

In the motion equations, apart from the specified forces, also the gravity force was taken into account.

3.1 Components of generalized external forces

The components of the external forces and their moments in the ship-fixed reference system are defined in each instant t by means of the following expressions [2] :

$$F_x=-m_\infty^{(1,1)}a_{Gx}-m_\infty^{(1,5)}\dot{\Omega}_y+$$
$$-\int_0^\infty r_{1,1}(\tau)V_x(t-\tau)\,d\tau-\int_0^\infty r_{1,5}(\tau)\,\Omega_y(t-\tau)\,d\tau+$$
$$+F_{Gx}+F_{Hx}+F_{Dx} \qquad (3.1)$$

$$F_y=-m_\infty^{(2,2)}a_{Gy}-m_\infty^{(2,4)}\Omega_x-m_\infty^{(2,6)}\dot{\Omega}_z+$$
$$-\int_0^\infty r_{2,2}(\tau)V_y(t-\tau)\,d\tau-\int_0^\infty r_{2,4}(\tau)\,\Omega_x(t-\tau)\,d\tau+$$
$$-\int_0^\infty r_{2,6}(\tau)\,\Omega_z(t-\tau)\,d\tau+F_{Gy}+F_{Hy}+F_{Dy} \qquad (3.2)$$

$$F_z = -m_{\infty}^{(3,3)} a_{Gz} - m_{\infty}^{(3,5)} \dot{\Omega}_y + \\ -\int_0^{\infty} r_{3,3}(\tau)\, V_z(t-\tau)\, d\tau - \int_0^{\infty} r_{3,5}(\tau)\, \Omega_y(t-\tau)\, d\tau + \\ + F_{Gz} + F_{Hz} + F_{Dz} \tag{3.3}$$

$$M_x = -m_{\infty}^{(4,2)} a_{Gy} - m_{\infty}^{(4,4)} \dot{\Omega}_x - m_{\infty}^{(4,6)} \dot{\Omega}_z + \\ -\int_0^{\infty} r_{4,2}(\tau)\, V_y(t-\tau)\, d\tau - \int_0^{\infty} r_{4,4}(\tau)\, \Omega_x(t-\tau)\, d\tau + \\ -\int_0^{\infty} r_{4,6}(\tau)\, \Omega_z(t-\tau)\, d\tau + M_{Hx} + M_{Dx} \tag{3.4}$$

$$M_y = -m_{\infty}^{(5,1)} a_{Gx} - m_{\infty}^{(5,3)} a_{Gz} - m_{\infty}^{(5,5)} \dot{\Omega}_y + \\ -\int_0^{\infty} r_{5,1}(\tau) V_y(t-\tau)\, d\tau - \int_0^{\infty} r_{5,3}(\tau)\, \Omega_x(t-\tau)\, d\tau + \\ -\int_0^{\infty} r_{5,5}(\tau)\, \Omega_z(t-\tau)\, d\tau + M_{Hy} + M_{Dy} \tag{3.5}$$

$$M_z = -m_{\infty}^{(6,2)} a_{Gy} - m_{\infty}^{(6,4)} \dot{\Omega}_x - m_{\infty}^{(6,6)} \dot{\Omega}_z + \\ -\int_0^{\infty} r_{6,2}(\tau) V_y(t-\tau)\, d\tau - \int_0^{\infty} r_{6,4}(\tau)\, \Omega_x(t-\tau)\, d\tau + \\ -\int_0^{\infty} r_{6,6}(\tau)\, \Omega_z(t-\tau)\, d\tau + M_{Hz} + M_{Dz} \tag{3.6}$$

where, generally :

$m_{\infty}^{i,j}$ – ship added masses for the infinite frequency
$r_{i,j}$ – memory functions
F_{Gk} – components of gravity force
F_{Hk} – components of Froude-Krilov's forces
F_{Dk} – components of diffraction forces
M_{Hk} – components of moment of Froude-Krilov's forces
M_{Dk} – components of moment of diffraction forces.

4. EQUATIONS OF UNDAMAGED SHIP MOTION

In the presented mathematical model water is considered as the ideal liquid. The assumption makes that forces and moments associated with viscosity of water are neglected. This way some really occurring phenomena such as e.g. the influence of bilge keels-usually applied to ro-ro ships - on ship's rolling, or on lateral resistance of a drifting ship, are neglected.

Therefore it is necessary to account for some additional forces and their moments, which especially affects ship's rolling and yawing motions.

4.1 Additional components of motion equations

Resistance of ship's side area

On the basis of computer simulations as well as observations from model basin tests it can be stated that a ship subject to action of diagonal or beam waves drifts with the velocity which becomes constant after some time. Thereby a lateral resistance force appears. The horizontal component of the force which should be additionally accounted for in the equation of rolling is as follows :

$$F_{By} = -\rho |V_y| V_y L_{pp} (T_s + T_b)/2 \tag{4.1}$$

Similarly, in the equation of yawing the moment of the lateral resistance force, associated with ship's rotation in the horizontal plane, should be accounted for :

$$M_{Bz} = -\rho |\Omega_z| \Omega_z L_{pp}^3 (T_s + T_b)/24 \tag{4.2}$$

where :
ρ – density of water
L_{pp} – ship length between perpendiculars
T_s – stern draught of ship (at A.P.)
T_b – bow draught of ship (at F.P.)
V_y – velocity component of oscillations of ship's gravity centre, along Oy axis
Ω_z – component of angular velocity vector.

The quantities T_s and T_b appearing in (4.1) and (4.2) are constant, and determined for a damaged ship in the state of equilibrium.

Damping of rolling

The bilge keels belong to the simplest, and simultaneously most often used, devices to stabilize ship's rolling. Hence possible presence of bilge keels should be optionally accounted for in the considered model. An appropriate computational solution was proposed by Ikeda [5] :

$$(M_{IK})_x = -(r_{4,4,1} + r_{4,4,2} |\Omega_x|)\, \Omega_x \tag{4.3}$$

where : $r_{4,4,1}$ and $r_{4,4,2}$ – Ikeda's coefficients accounting for nonlinear effects due to bilge keels.

4.2 Equations of translational motion

On the basis of (2.2) and (3.1) and after accounting for (4.1) the following three equations of translation motion, in a form convenient for numerical integration, are obtained :

$$\left(m + m_{\infty}^{(1,1)}\right) \dot{V}_x + m_{\infty}^{(1,5)} \dot{\Omega}_y = -\left(m + m_{\infty}^{(1,1)}\right)\left(\Omega_y V_z - \Omega_z V_y\right) + \\ + \int_0^{\infty} r_{1,1}(\tau)\, V_x(t-\tau)\, d\tau - \int_0^{\infty} r_{1,5}(\tau)\, \Omega_y(t-\tau)\, d\tau + \\ + F_{Gx} + F_{Hx} + F_{Dx} \tag{4.4}$$

$$\left(m+m_{\infty}^{(2,2)}\right)\dot{V}_y+m_{\infty}^{(2,4)}\dot{\Omega}_x+m_{\infty}^{(2,6)}\dot{\Omega}_z=$$
$$=-\left(m+m_{\infty}^{(2,2)}\right)\left(\Omega_z V_x-\Omega_x V_z\right)+$$
$$-\int_0^{\infty} r_{2,2}(\tau)\,V_y(t-\tau)\,d\tau-\int_0^{\infty} r_{2,4}(\tau)\,\Omega_x(t-\tau)\,d\tau+$$
$$-\int_0^{\infty} r_{2,6}(\tau)\,\Omega_z(t-\tau)\,d\tau+m\,g\sin\varphi+F_{Hy}+F_{Dy}+F_{By} \qquad (4.5)$$

$$\left(m+m_{\infty}^{(3,3)}\right)\dot{V}_z+m_{\infty}^{(3,5)}\dot{\Omega}_y=$$
$$=-\left(m+m_{\infty}^{(3,3)}\right)\left(\Omega_x V_y-\Omega_y V_x\right)+$$
$$-\int_0^{\infty} r_{3,3}(\tau)\,V_z(t-\tau)\,d\tau-\int_0^{\infty} r_{3,5}(\tau)\,\Omega_y(t-\tau)\,d\tau+$$
$$+m\,g\cos\varphi+F_{Hz}+F_{Dz} \qquad (4.6)$$

4.3 Equations of rotational motion

After inserting the equations (3.4), (3.5) and (3.6) into the equation (2.5) and accounting for the moments of the additional forces given by the formulae (4.2) and (4.3), and some transformations, the following set of rotational motion equations suitable for numerical integration, is obtained :

$$m_{\infty}^{(4,2)}\dot{V}_y+\left(I_x+m_{\infty}^{(4,4)}\right)\dot{\Omega}_x+m_{\infty}^{(4,6)}\dot{\Omega}_z=$$
$$=-m_{\infty}^{(4,2)}\left(\Omega_z V_x-\Omega_x V_z\right)-\int_0^{\infty} r_{4,2}(\tau)V_y(t-\tau)\,d\tau+$$
$$-\int_0^{\infty} r_{4,4}(\tau)\,\Omega_x(t-\tau)\,d\tau+$$
$$-\int_0^{\infty} r_{4,6}(\tau)\,\Omega_z(t-\tau)\,d\tau+M_{Hx}+M_{Dx}+(M_{IK})_x \qquad (4.7)$$

$$m_{\infty}^{(5,1)}\dot{V}_x+m_{\infty}^{(5,3)}\dot{V}_z+\left(I_L+m_{\infty}^{(5,5)}\right)\dot{\Omega}_y=$$
$$=\left(I_L-I_x\right)\Omega_z\Omega_x+$$
$$-m_{\infty}^{(5,1)}\left(\Omega_y V_z-\Omega_z V_y\right)-m_{\infty}^{(5,3)}\left(\Omega_x V_y-\Omega_y V_x\right)+$$
$$-\int_0^{\infty} r_{5,1}(\tau)\,V_x(t-\tau)\,d\tau-\int_0^{\infty} r_{5,3}(\tau)\,V_z(t-\tau)\,d\tau+$$
$$-\int_0^{\infty} r_{5,5}(\tau)\,\Omega_y(t-\tau)\,d\tau+M_{Hy}+M_{Dy} \qquad (4.8)$$

$$m_{\infty}^{(6,2)}\dot{V}_y+m_{\infty}^{(6,4)}\dot{\Omega}_x+\left(I_L+m_{\infty}^{(6,6)}\right)\dot{\Omega}_z=$$
$$=-\left(I_L-I_x\right)\Omega_x\Omega_y-m_{\infty}^{(6,2)}\left(\Omega_z V_x-\Omega_x V_z\right)+$$
$$-\int_0^{\infty} r_{6,2}(\tau)\,V_y(t-\tau)\,d\tau-\int_0^{\infty} r_{6,4}(\tau)\,\Omega_x(t-\tau)\,d\tau+$$
$$-\int_0^{\infty} r_{6,6}(\tau)\,\Omega_z(t-\tau)\,d\tau+M_{Hz}+M_{Dz}+M_{Bz} \qquad (4.9)$$

4.4 Final form of motion equations of undamaged ship

The equations (2.3), (2.6), (4.4) ÷ (4.9) form the set of twelve ordinary 1st - order differential equations in respect to the linear displacements *R*, angular displacements α, linear velocities *V* and angular velocities Ω, which unambiguously describe the undamaged ship's spatial motion. They form the so called set of the state. By integrating the equations the simulation of ship motions in waves can be obtained. An important problem in solving them is the determination of the hydrodynamic forces and moments appearing in the right sides of the equations (4.4) ÷ (4.9).

5. FORCES GENERATED BY OUTBOARD WATER INSIDE DAMAGED SHIP

5.1 Vectorial tensor-by-vector multiplication

In order to simplify the derivation of the expressions appearing in the damaged ship's motion equations as well as to give them a simpler form, the symbolic vectorial tensor-by-vector multiplication has been introduced, in result of which a new tensor is obtained, shortly described as follows :

$$D=[C\otimes w] \qquad (5.1)$$

where :

D, C – 3 x 3 tensors
w – vector.

The tensor [C ⊗ w] is defined as follows :

$$D=\begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}\otimes\begin{bmatrix} w_x \\ w_y \\ w_z \end{bmatrix}=$$
$$=\begin{bmatrix} c_{21}w_z-c_{31}w_y & c_{22}w_z-c_{32}w_y & c_{23}w_z-c_{33}w_y \\ c_{31}w_x-c_{11}w_z & c_{32}w_x-c_{12}w_z & c_{33}w_x-c_{13}w_z \\ c_{11}w_y-c_{21}w_x & c_{12}w_y-c_{22}w_x & c_{13}w_y-c_{23}w_x \end{bmatrix} \qquad (5.2)$$

It can be observed that the elements of the matrix *D* are the determinants of the sucessive 2 x 2 matrices formed of the incomplete column of the tensor *C* and the incomplete vector *w*. Knowing the symbolic multiplication rule one can easily form the *D*-matrix elements.

5.2 Forces and moments of inertia of water contained in damaged ship

In order to determine the forces and moments of inertia due to the outboard water contained in a damaged ship's hull, which give dynamic effects, the following considerations should be taken into account.

The position of the mass element of the water contained inside damaged ship's hull, dm_w, is determined by the radius-vector *r* given in the hull's reference system whose centre is located in the undamaged ship's centre of gravity, *G*. The velocity of the mass element *dm* is equal to that of the ship's centre of gravity, enlarged by the change rate of the radius-vector *r*. Therefore :

$$V_W = V_G + \Omega \times r + \dot{r} \tag{5.3}$$

where :

- V_W – water particle's velocity
- V_G – velocity of ship's gravity centre
- Ω – ship's angular velocity
- r – radius-vector of dm_w mass element of the water contained in damaged compartment, in respect to the ship's gravity centre *G*.

The mass element's acceleration in the ship-fixed reference system is described by the well known expression obtained by differentiating the formula (5.3) :

$$a = a_G + \dot{\Omega} \times r + \Omega \times (\Omega \times r) + 2\Omega \times \dot{r} + \ddot{r} \tag{5.4}$$

where :

a_G – acceleration of the ship's gravity centre *G*.

The second component of the above given formula is the tangential acceleration, the third – the centripetal acceleration, and the fourth – the Coriolis acceleration. Because the ship's angular velocities are small the nonlinear term associated with the centripetal acceleration is a small second-order quantity and thereby it can be neglected. Such reasoning cannot be applied to the tangential acceleration as – in general – change rates of small quantities need not to be small too. And, the last component expresses that the water is not a solid body, it moves inside a damaged hull generating some relative accelerations, i.e. the dynamic effects which cannot be neglected.

In order to facilitate calculations, the two last components, i.e. the Coriolis acceleration and the relative acceleration should be estimated analytically on the basis of the motion of the water in flooded compartments. The water in flooded compartments is considered in a quasi-static way. Its free surface is assumed flat and normal to the instantaneous acceleration of the gravity centre of the water, (*g* – *a*), present both below and above the ro-ro ship's car deck.

It is difficult to determine the relative velocity and acceleration of every water particle. However the quantities can be easily determined for the volumetric centre of the water in flooded compartment. In one time-step the acceleration of the gravity volumetric centre is defined by the following equation :

$$\begin{aligned} dr_0 &= BM\, d\alpha_W b - BL\, d\alpha_W e = \\ &= BM\, d\alpha_W \times n - BL\, d\alpha_W \end{aligned} \tag{5.5}$$

where :

- BM – metacentric radius of the outboard water contained in damaged compartment
- BL – deviation radius of the water in damaged compartment
- e – versor of water surface rotation axis in the compartment
- n – versor normal to the water surface inside the hull, pointed along the vector (*g* – *a*)
- b – (*e* × *n*) vector tangent to the projection of the trajectory of the water gravity centre, on the plane normal to the instantaneous rotation axis *e*
- $d\alpha_W$ – relative free-surface rotation angle.

The formula (5.5) deals with the equivolumetric rotations, and it is derived on the basis of the relationships known from the theory of ships [1]. By differentiating the formula (5.5) in respect to time the velocity and acceleration vectors of the gravity centre of the water in damaged compartment, relative to ship, can be expressed, respectively, as follows :

$$\begin{aligned} \dot{r}_0 &= BM\, \dot{\alpha}_W \times n - BL\, \dot{\alpha}_W \\ \ddot{r}_0 &= BM\, \ddot{\alpha}_W \times n - BL\, \ddot{\alpha}_W \end{aligned} \tag{5.6}$$

If the vector Ω is horizontal the water surface rotation velocity in respect to ship, $\dot{\alpha}_W$, will be equal to ($-\Omega$). In general, the ship angular velocity Ω may be of an arbitrary direction, not being the same as that of the axis of the water surface rotation inside ship, having *e* versor. The vector $\dot{\alpha}_W$, is equal to the projection of the vector ($-\Omega$) onto the rotation axis *e*. Hence :

$$\begin{aligned} \dot{\alpha}_W &= -(\Omega \cdot e)e = -E\Omega \\ \ddot{\alpha}_W &= -(\dot{\Omega} \cdot e)e = -E\dot{\Omega} \end{aligned} \tag{5.7}$$

where :

$E = (e \otimes e) = e_{ij} = e_i e_j$ is the symmetrical dyad formed by the *e* - versors of the water surface rotation axis. Having accounted for (5.7) in the formula (5.6) one can eventually obtain :

$$\begin{aligned} \dot{r}_0 &= -BM(E\Omega) \times n + BL(E\Omega) \\ \ddot{r}_0 &= -BM(E\dot{\Omega}) \times n + BL(E\dot{\Omega}) \end{aligned} \tag{5.8}$$

Now it can be observed that in the formula (5.4) the Coriolis acceleration may be ommitted as being a small 2^{nd} order quantity, thereby the number of components is reduced to three, hence :

$$a = a_G + \dot{\Omega} \times r + \ddot{r} \tag{5.9}$$

On the basis of the above presented considerations it can be stated that the below given formula represents the magnitude of the apparent external force resulting from dynamic action of water contained inside a damaged ship's hull :

$$\begin{aligned} F_W &= -\int a\, dm_W = -\int [a_G + \dot{\Omega} \times r + \ddot{r}]\, dm_W = \\ &= -a_G \int dm_W - \dot{\Omega} \times \int r\, dm_W - \ddot{r} \int dm_W = \\ &= -m_W [a_G + \dot{\Omega} \times r_0 + \ddot{r}_0] \end{aligned} \tag{5.10}$$

where :

- m_W – instantaneous mass of water in a flooded compartment
- r_0 – radius-vector of the volumetric centre of water in a flooded compartment, in respect to the ship centre of gravity.

Analogically to the formula (5.10) the moment of effects of outboard water mass in a flooded compartment, can be determined :

$$\begin{aligned} M_W &= -\int r \times a\, dm_W = -\int r \times [a_G + \dot{\Omega} \times r + \ddot{r}]\, dm_W = \\ &= -\int r\, dm_W \times a_G - \int r \times (\dot{\Omega} \times r)\, dm_W - \int r\, dm_W \times \ddot{r}_o = \\ &= -M_G \times a_G - J_G \dot{\Omega} - M_G \times \ddot{r}_o \end{aligned} \tag{5.11}$$

where :

J_G – tensor of mass inertia of water in a flooded compartment.

5.3 Rotation axis versor

The versor of the rotation axis, e, is determined by the projection of the ship's angular velocity vector Ω onto the horizontal plane (i.e. water surface). The projection is expressed as follows :

$$\begin{aligned}\Omega_s &= n \times (\Omega \times n) = \\ &= \Omega - n\,(n \cdot \Omega) = [I - N] = S\Omega\end{aligned} \tag{5.12}$$

where :

I – unit tensor

$N = (n \otimes n) = n_{ij} = n_i n_j$ – the symmetrical dyad formed by the versors normal to water surface.

5.4 Scalar components of the forces and moments due to the outboard water inside the ship

In order to obtain the scalar components of the forces and moments due to the outboard water inside the ship it is necessary to sucessively describe the components contained in the formulae (5.10) and (5.11) with the use of the introduced operation of the vectorial tensor-by-vector multiplication. After many transformations the following is obtained :

$$\begin{aligned}F_{wx} &= -m_w a_x + \\ &+\rho(I_{TT}d_{11} - I_{TL}e_{11})\dot{\Omega}_x + \\ &-[M_{Gz} - \rho(I_{TT}d_{12} - I_{TL}e_{12})]\dot{\Omega}_y + \\ &+[M_{Gy} + \rho(I_{TT}d_{13} - I_{TL}e_{13})]\dot{\Omega}_z\end{aligned} \tag{5.13}$$

$$\begin{aligned}F_{wy} &= -m_w a_y + \\ &+[M_{Gz} + \rho(I_{TT}d_{21} - I_{TL}e_{21})]\dot{\Omega}_x + \\ &+\rho(I_{TT}d_{22} - I_{TL}e_{22})\dot{\Omega}_y + \\ &-[M_{Gx} - \rho(I_{TT}d_{23} - I_{TL}e_{23})]\dot{\Omega}_z\end{aligned} \tag{5.14}$$

$$\begin{aligned}F_{wz} &= -m_w a_z + \\ &-[M_{Gy} - \rho(I_{TT}d_{31} - I_{TL}e_{31})]\dot{\Omega}_x + \\ &+[M_{Gx} + \rho(I_{TT}d_{32} - I_{TL}e_{32})]\dot{\Omega}_y + \\ &+\rho(I_{TT}d_{33} - I_{TL}e_{33})\dot{\Omega}_z\end{aligned} \tag{5.15}$$

$$\begin{aligned}M_{wx} &= -M_{Gy}a_z + M_{Gz}a_y + \\ &-[I_{wx} + \rho(I_{TT}q_{11} - I_{TL}s_{11})]\dot{\Omega}_x + \\ &+[D_{wy} - \rho(I_{TT}q_{12} - I_{TL}s_{12})]\dot{\Omega}_y + \\ &+[D_{wz} - \rho(I_{TT}q_{13} - I_{TL}s_{13})]\dot{\Omega}_z\end{aligned} \tag{5.16}$$

$$\begin{aligned}M_{wy} &= -M_{Gz}a_x + M_{Gx}a_z + \\ &+[D_{wx} - \rho(I_{TT}q_{21} - I_{TL}s_{21})]\dot{\Omega}_x + \\ &-[I_{wy} + \rho(I_{TT}q_{22} - I_{TL}s_{22})]\dot{\Omega}_y + \\ &+[D_{wz} - \rho(I_{TT}q_{23} - I_{TL}s_{23})]\dot{\Omega}_z\end{aligned} \tag{5.17}$$

$$\begin{aligned}M_{wz} &= -M_{Gx}a_y + M_{Gy}a_x + \\ &+[D_{wx} - \rho(I_{TT}q_{31} - I_{TL}s_{31})]\dot{\Omega}_x + \\ &+[D_{wy} - \rho(I_{TT}q_{32} - I_{TL}s_{32})]\dot{\Omega}_y + \\ &-[I_{wz} + \rho(I_{TT}q_{33} - I_{TL}s_{33})]\dot{\Omega}_z\end{aligned} \tag{5.18}$$

where :

d_{ij}, s_{ij}, q_{ij} – elements of tensors obtained from tensor-by-vector multiplication

I_{TT} – inertia moment of area of water surface in a damaged compartment, in respect to the ship's rotation axis e

I_{TL} – deviation moment.

In the case when the free water surface is composed of two parts : that in the damaged compartment on the car deck and that below the car deck, the moments are equal to the sum of the moments derived for each of the compartments separately.

And :

I_{wx}, I_{wy}, I_{wz} – inertia moments of mass of water inside a ship's hull

D_{wx}, D_{wy}, D_{wz} – deviation moments of mass of water inside a ship's hull.

5.5 Additional components of the damaged ship's motion equations

The above presented mathematical model does not take into account some really occurring phenomena such as an additional resistance due to immerging and emerging the car deck within a damaged part of ship's hull, or a jet force associated with water flowing to and out the damaged ship's interior. An important element which has to be taken into account in the damaged ship's motion equations, is an appropriate representation of the damping induced by the water inside the damaged hull.

Water jet force

During ship's motion in waves we deal with a changeable mass of water contained in flooded compartments. In this connection an additional force appears which may be considered as a water jet force being a water reaction in a hole, associated with water flow through the hole. The reaction is given by the following formula :

$$R_{ry} = -\rho A |V_w| V_w \tag{5.19}$$

where :

A – area of a part of the hole through which water flow occurs

V_w – water velocity in the hole.

The reaction should be accounted for in the equation concerning ship's rolling. For completeness, in this equation accounted for should be the moment due to the water-in-hole reaction, which can be determined as follows :

$$M_{rx} = R_{ry}(Z_G - Z_W) \tag{5.20}$$

where :

Z_G – distance of the ship's centre of gravity, G, from the reference plane

Z_W – distance, from the reference plane, of the geometrical centre of area of a part of the hole through which the water flow occurs.

Car deck reaction

Let's assume that during damaged ship's motion its car deck is immersed. In this case an additional force occurs which can be most simply determined by applying the principle of conservation of momentum. Its moment in respect to the Ox-axis of the ship-fixed reference system, which should be additionally accounted for in the ship's rolling equation, is expressed by the formula [9] :

$$M_{dx} = \rho \int_A V_z^2 y dA \tag{5.21}$$

Damping forces due to water inside damaged ship

From model tests it results that the presence of outboard water in damaged compartments is of a great importance for damping ship's rolling. Some computer tests confirmed that in the damaged ship's motion equations the water damping effects should be accounted for by means of an additional component which can be determined with the following empirical formula :

$$M_{tx} = -0.333 \frac{I_{TT}}{I_B} \frac{r_B}{GM} N_{4,4} \Omega_x \tag{5.22}$$

where :

- I_{TT} – transverse inertia moment of free surface area in a compartment
- I_B – transverse inertia moment of ship waterplane area
- r_B – transverse metacentric radius of damaged ship
- GM – transverse metacentric height of damaged ship
- $N_{4,4}$ – damping coefficient for natural frequency of rolling.

The quantities : I_B , r_B and GM appearing in the formula (5.22) are assumed for undamaged ship in the state of equilibrium. The so calculated M_{tx} value should be applied to each of the damaged compartments separately.

6. FINAL FORM OF DAMAGED SHIP'S MOTION EQUATIONS

The damaged ship's motion equations were obtained after supplementing the above presented (in p. 4.4) motion equations of undamaged ship by :

- the forces given by (5.13) ÷ (5.15)
- the moments of the forces induced by the water contained in damaged compartments, given by (5.16) ÷ (5.18), as well as
- all the additional components described in pp. 4.1 and 5.5.

After these operations the damaged ship's motion equations take the following form :

for surging :

$$\begin{aligned}
&\left(m + m_w + m_\infty^{(1,1)}\right)\dot{V}_x + \\
&-\rho(I_{TT}d_{11} - I_{TL}e_{11})\,\dot{\Omega}_x + \\
&+[M_{wz} - \rho(I_{TT}d_{12} - I_{TL}e_{12}) + m_\infty^{(1,5)}]\,\dot{\Omega}_y + \\
&-[M_{wy} + \rho(I_{TT}d_{13} - I_{TL}e_{13})]\,\dot{\Omega}_z = \\
&= -\left(m + m_w + m_\infty^{(1,1)}\right)\left(\Omega_y V_x - \Omega_x V_y\right) + \\
&-\int_0^\infty r_{1,1}(\tau)V_x(t-\tau)\,d\tau - \int_0^\infty r_{1,5}(\tau)\,\Omega_x(t-\tau)\,d\tau + \\
&-(m + m_w)\,g\theta + F_{Hy} + F_{Dy}
\end{aligned} \tag{6.1}$$

for rolling :

$$\begin{aligned}
&\left(m + m_w + m_\infty^{(2,2)}\right)\dot{V}_y + \\
&+\left[-\rho(I_{TT}d_{21} - I_{TL}e_{21}) - M_{wz} + m_\infty^{(2,4)}\right]\dot{\Omega}_x + \\
&-\rho(I_{TT}d_{22} - I_{TL}e_{22})\,\dot{\Omega}_y + \\
&+\left[M_{wx} - \rho(I_{TT}d_{23} - I_{TL}e_{23}) + m_\infty^{(2,6)}\right]\dot{\Omega}_z = \\
&= -\left(m + m_w + m_\infty^{(2,2)}\right)(\Omega_z V_x - \Omega_x V_z) + \\
&-\int_0^\infty r_{2,2}(\tau)V_y(t-\tau)\,d\tau - \int_0^\infty r_{2,4}(\tau)\,\Omega_x(t-\tau)\,d\tau + \\
&-\int_0^\infty r_{2,6}(\tau)\,\Omega_z(t-\tau)\,d\tau + \\
&+(m + m_w)\,g\sin\varphi + F_{Hy} + F_{Dy} + R_{ry} + F_{By}
\end{aligned} \tag{6.2}$$

for heaving :

$$\begin{aligned}
&\left(m + m_w + m_\infty^{(3,3)}\right)\dot{V}_z + \\
&+\left[M_{wy} - \rho(I_{TT}d_{31} - I_{TL}e_{31})\right]\dot{\Omega}_x + \\
&+\left[-\rho(I_{TT}d_{32} - I_{TL}e_{32}) - M_{wx} + m_\infty^{(3,5)}\right]\dot{\Omega}_y + \\
&-\rho(I_{TT}d_{33} - I_{TL}e_{33})\,\dot{\Omega}_z = \\
&= -\left(m + m_w + m_\infty^{(3,3)}\right)(\Omega_x V_y - \Omega_y V_x) + \\
&-\int_0^\infty r_{3,3}(\tau)V_z(t-\tau)\,d\tau - \int_0^\infty r_{3,5}(\tau)\,\Omega_y(t-\tau)\,d\tau + \\
&+(m + m_w)\,g\cos\varphi + F_{Hz} + F_{Dz}
\end{aligned} \tag{6.3}$$

for drifting :

$$\begin{aligned}
&\left(m_\infty^{(4,2)} - M_{wz}\right)\dot{V}_y + M_{wy}\dot{V}_z + \\
&+\left[I_x + I_{wx} - \rho(I_{TT}q_{11} - I_{TL}s_{11}) + m_\infty^{(4,4)}\right]\dot{\Omega}_x + \\
&-\left[D_{xy} - \rho(I_{TT}q_{12} - I_{TL}s_{12})\right]\dot{\Omega}_y + \\
&+\left[\rho(I_{TT}q_{13} - I_{TL}s_{13}) - D_{xz} + m_\infty^{(4,6)}\right]\dot{\Omega}_z = \\
&= -\left(m_\infty^{(4,2)} - M_{wz}\right)(\Omega_z V_x - \Omega_x V_z) + \\
&-M_{wy}\left(\Omega_x V_y - \Omega_y V_x\right) - \int_0^\infty r_{4,2}(\tau)V_y(t-\tau)\,d\tau + \\
&-\int_0^\infty r_{4,4}(\tau)\,\Omega_x(t-\tau)\,d\tau - \int_0^\infty r_{4,6}(\tau)\,\Omega_z(t-\tau)\,d\tau + \\
&+M_{Hx} + M_{Dx} + m_w g(y_o\cos\varphi - z_o\sin\varphi) + \\
&+M_{rx} + (\dot{M}_{Ik})_x + M_{dx} + M_{tx}
\end{aligned} \tag{6.4}$$

for pitching :

$$
\begin{aligned}
&\left(M_{wz}+m_{\infty}^{(5,1)}\right)\dot{V}_x-\left(M_{wx}-m_{\infty}^{(5,3)}\right)\dot{V}_z+\\
&-\left[D_{yx}-\rho\left(I_{TT}q_{21}-I_{TL}s_{21}\right)\right]\dot{\Omega}_x+\\
&+\left(I_L+I_{wy}+\rho\left(I_{TT}q_{22}-I_{TL}s_{22}\right)+m_{\infty}^{(5,5)}\right)\dot{\Omega}_y+\\
&-\left[D_{yz}-\rho\left(I_{TT}q_{23}-I_{TL}s_{23}\right)\right]\dot{\Omega}_z=\\
&=\left(I_L-I_x\right)\Omega_z\Omega_x\\
&-\left(M_{wz}+m_{\infty}^{(5,1)}\right)\left(\Omega_y V_z-\Omega_z V_y\right)+\\
&+\left(M_{wx}-m_{\infty}^{(5,3)}\right)\left(\Omega_x V_y-\Omega_y V_x\right)+\\
&-\int_0^{\infty} r_{5,1}(\tau)V_x(t-\tau)\,d\tau-\int_0^{\infty} r_{5,3}(\tau)V_z(t-\tau)\,d\tau+\\
&-\int_0^{\infty} r_{5,5}(\tau)\,\Omega_y(t-\tau)\,d\tau+M_{Hy}+M_{Dy}+\\
&-m_w g\left(z_o\theta+x_o\cos\varphi\right)
\end{aligned}
\qquad (6.5)
$$

for yawing :

$$
\begin{aligned}
&-M_{wy}\dot{V}_x+\left(M_{wx}+m_{\infty}^{(6,2)}\right)\dot{V}_y+\\
&-\left[D_{zx}-\rho\left(I_{TT}q_{31}-I_{TL}s_{31}\right)-m_{\infty}^{(6,4)}\right]\dot{\Omega}_x+\\
&-\left[D_{zy}-\rho\left(I_{TT}q_{32}-I_{TL}s_{32}\right)\right]\dot{\Omega}_y+\\
&+\left(I_L+I_{wz}+\rho\left(I_{TT}q_{33}-I_{TL}s_{33}\right)+m_{\infty}^{(6,6)}\right)\dot{\Omega}_z=\\
&=-\left(I_L-I_x\right)\Omega_x\Omega_y+M_{wy}\left(\Omega_y V_z-\Omega_z V_y\right)+\\
&-\left(M_{wx}+m_{\infty}^{(6,2)}\right)\left(\Omega_z V_x-\Omega_x V_z\right)+\\
&-\int_0^{\infty} r_{6,2}(\tau)V_y(t-\tau)\,d\tau-\int_0^{\infty} r_{6,4}(\tau)\,\Omega_x(t-\tau)\,d\tau+\\
&-\int_0^{\infty} r_{6,6}(\tau)\,\Omega_z(t-\tau)\,d\tau+M_{Hz}+M_{Dz}+\\
&+m_w g\left(x_o\sin\varphi+y_o\theta\right)
\end{aligned}
\qquad (6.6)
$$

7. DISCUSSION OF THE SET OF THE SHIP MOTION EQUATIONS

The equations (2.3), (2.6), (6.1) ÷ (6.6) form the set of twelve ordinary 1st order differential equations in respect to the linear displacements R, angular displacements α , linear velocities V and angular velocities Ω, which unambiguously describes damaged ship's motion in space. By integrating the equations a simulation of damaged ship's motions is obtained.

The motion equations of undamaged ship in waves, presented in p. 4.4 as well as those of damaged ship, given in p.6, which form the set of 12 ordinary differential equations, are coupled and highly nonlinear. The ship motions corresponding to particular degrees of freedom influence each other. This results from the form of the equations itself. However, the couplings reside first of all in the right sides of the equations of dynamics as well as in the rotational motion equations.

Solving the set of the motion equations is difficult due to its nonlinearity. The nonlinearity lies in the form of the equations and in the character of hydrodynamical forces which, for large ship's motions, are nonlinear functions of motion parameters, yet amplified by the geometrical nonlinearity associated with ship's hull form.

The set of the ship motion equations can be itegrated only numerically. With this end in view a procedure based on Hamming's method was applied. It is multi-step extrapolation-interpolation method of 4th order, supplemented by the Runge-Kutta's method to calculate starting values [11].

By using the procedure an integration step is automatically chosen by dividing in half and doubling the basic step until a demanded calculation accuracy is obtained.

In each time-step the forces and moments appearing in the right sides of the equations, considered as explicit functions of time, are determined. During the calculations an instantaneous position of a ship as well as a form of immersed part of ship's hull, associated with such position, are to be accounted for.

8. FINAL REMARKS

- On the basis of the presented mathematical model the computer software called KOŁYSANIA was developed [7]. It realizes the numerical simulation of ro-ro ship's motions in irregular waves. The program has been thoroughly tested and hence it can serve as a fully functional, user's friendly instrument for carrying out projects dealing with prediction of the behaviour of damaged and undamaged ships in waves.
- The described mathematical model and the mentioned, based on it, computer software are deemed to be of an essential practical importance. Such opinion comes from the till now obtained results [4] as well as from the fact that the model basin experiments are ill-conditioned and expensive. Moreover, they are labour and time consuming. On the contrary, preparation of data for computer simulations is rather not burdensome, and the appropriate calculations can be performed, if possible, with the use of a few computers simultaneously.
- Today, there are no other reliable methods for predicting ship's behaviour in irregular waves and for analizing conditions leading to its capsizing.
- The applied graphical presentation of computer calculation results makes it possible to interprete them qualitatively and to draw practical conclusions regarding the damaged ship's behaviour in heavy seas, and course of its sinking.

Appraised by Maciej Pawłowski, Assoc.Prof.,D.Sc.

NOMENCLATURE

a	–	acceleration of mass element
a_G	–	acceleration of the ship's gravity centre G
A	–	area of a part of the hole through which water flow occurs
b	–	($e \times n$) vector tangent to the projection of the trajectory of the water gravity centre, on the plane normal to the instantaneous rotation axis e
d_{ij}, s_{ij}, q_{ij}	–	elements of tensors obtained from tensor-by-vector multiplication
dm_w	–	mass element of water in a damaged compartment
D_w	–	deviation moment of mass of water inside a ship's hull
e	–	versor of water surface rotation axis in a damaged compartment
e_{ij}	–	elements of the symmetrical dyad formed by the e - versors of the water surface rotation axis
F	–	resultant external force exerted on a ship
F_{By}	–	component of ship's lateral resistance force
F_D	–	diffraction force
F_G	–	gravity force
F_H	–	Froude-Krilov's force
F_w	–	force due to dynamic action of the water inside damaged ship's hull
g	–	gravity acceleration vector
I_{TL}	–	deviation moment of free surface area in a damaged compartment
I_{TT}	–	transverse inertia moment of free surface area in a damaged compartment, relative to its rotation axis

I_w – inertia moment of mass of water inside a damaged compartment
I_x, I_L – ship's moments of inertia
m – mass of a ship
m_w – instantaneous mass of water in a flooded compartment
$m^{i,j}_{\infty}$ – ship added mass components for the infinite frequency
M – moment of resultant external force exerted on a ship
M_{Bz} – moment of ship's lateral resistance force
M_{dx} – component of car deck reaction moment
M_D – moment of diffraction force
M_G – vector of statical moment due to mass of water contained in a damaged compartment
M_H – moment of Froude – Krilov's force
$(M_{Ik})_x$ – component of roll damping moment, acc. Ikeda
M_{rx} – component of water reaction force in a hole
M_{tx} – component moment of damping of water contained in a damaged compartment
M_w – moment of dynamic force due to water action inside a damaged ship
r – radius-vector of dm_w mass element of the water contained in a damaged compartment, in respect to the ship's gravity centre *G*
$r_{i,j}$ – memory functions
r_0 – radius-vector of the volumetric centre of water in a flooded compartment, in respect to the ship centre of gravity, *G*
R – vector of translations of the ship's centre of gravity, *G*, around its average position
R_{ry} – component of water jet force
t, τ – time
V – oscillation velocity of the ship's centre of gravity, *G*, around its average position
V_G – velocity of ship's gravity centre
V_w – water velocity in a hole
V_y – component of oscillation velocity of the ship's centre of gravity G
x, y, z – indices of vector components of : translations of ship's gravity centre G, forces, moments, velocities, accelerations, in Cartesian reference system
x_o, y_o, z_o – components of radius-vector, r_o

α – ship's rotation angle
α_w – rotation angle of free surface area
φ, θ, ψ – Euler's angles - components of ship's rotation angle α
ρ – density of outboard water
Ω – ship's angular velocity vector

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Conference

SAFERELNET

The thematic network under this shortened name, contained in 5th Outline Program of the European Union, deals with :

Safety and Reliability of Industrial Products and Structures*

In the realization of the program the Ship Design & Research Centre (CTO), Gdańsk, has taken part, together with other Polish partners. Hence on 26 May 2003 it organized the Public Workshop on :

Safety and Reliability in Waterborne Transport

For the meeting 14 papers were arranged by 5 foreign authors and 13 Polish ones. The presentation of the papers was performed during 3 sessions :

Session 1 : **Safety and Reliability in Service**

- *Safety of high speed maritime transportation* – by P. Antão, A.Teixeria, C.Guedes Soares (Instituto Superior Técnico, Lisbon)
- *International regulations concerning ship and port facility security against terrorist attacks (ISPS Code)* by J. Dering (Polish Register of Shipping)
- *Safety and dependability in human activities at sea* by M. Kubacka, A. Jędrzejewska (Ship Design & Research Centre, Gdańsk)
- *Some problems of management of navigational safety in limited sea areas* – by J. Drobiszewski (Warsaw University of Technology), L. Gucma (Maritime University of Szczecin)
- *A model of direct risk assessment when ship is in critical conditions* – by M. Gerigk, (Gdańsk University of Technology)

Session 2 : **Design for Safety and Reliability**

- *SAFETY FIRST project – a step forward in passenger ship safety design* – by C. Vivalda, G. Chantelauve (Bureau Veritas)
- *Environmental safety of a seagoing ship's power plant* by A Brandowski, R. Liberacki (Gdańsk University of Technology)
- *Selected topics of podded ROPAX safety on the basis of EU project OPTIPOD* – by J. Kanar (Ship Design & Research Centre, Gdańsk)
- *Development of probabilistic damage stability regulations within the frames of HARDER project* – by P.Grzybowski (Ship Design & Research Centre, Gdańsk)
- *Hydrogen degradation of steels for ship hulls* by P. Domżalicki, (Ship Design & Research Centre, Gdańsk)

Session 3 : **Safety of Maritime Transportation**

- *Safety of navigation on extremely shallow inland waterways from the perspective of INBAT project* – by W. Górski, (Ship Design & Research Centre, Gdańsk)
- *Reliability of port transportation structures related to their operation processes* – by K. Kołowrocki, (Gdynia Maritime University)
- *A new ADMAR unit conception in ECDIS* by K. Kołowrocki, A. Weintrit, (Gdynia Maritime University)
- *Risk assessment of a maritime transportation system* by C. Guedes Soares, (Instituto Superior Técnico, Lisbon).

This part of the Workshop was preceded by visiting the Gdańsk Ship Model Basin and Fire Test Stand being an important part of CTO laboratories.

* *A more comprehensive information on the SAFERELNET network was published in the previous issue of this journal.*