Influence of flooding compartment on the ship’s safety

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***Abstract*—**Every damage to a ship results in certain effects, ie flooding water over one or more watertight compartments, which affects changes in stability and position of the ship. Determination of these changes is the basis for the sub-capacity calculations related to the operation of a damaged ship. During the ship's operation, unusual damage not anticipated in the stability documentation may occur, so it is necessary to know the methods of calculating the subdivision. During the ship's operation at sea a significant threat to his safety is a fire. Rarely causes sinking of the ship, however, the damage that it leaves is usually very serious and as always, depending on the level of crew training in the area of emergency response. The main extinguishing agent used on ships is usually sea water, which in large quantities poses a threat to the stability and submarine of the ship. Therefore, the main focus of the work was to determine the impact of flooding of high-stability compartments of the ship. The results of the calculations presented in the work include information on the amount of water in the range causing deterioration of the stability of the ship.

***Keywords*—**free surface effect, metacentric height, righting lever.

I. INTRODUCTION

SHIP is a compound technical system operated intensively in particular during military activities. Her combat abilities depend, first of all, on munitions with which the vessel is equipped and on the remaining technical measures ensuring her way [5]. Damages caused to those measures result in deterioration of the boat military capabilities and they may be followed by various reasons. Events causing damages to the ship, as to a technical system, are presented in Figure 1. Fire presents serious hazard to a ship when at sea. It results in her sinking rarely, however the left devastation is usually very serious and, as ever, depending on the level of the crew training in respect to the damage control plan. During peaceful operation of the combat vessel, short-circuits in electrical installations, failures of devices and mechanisms, self ignition of pure oxygen when contacted with petroleum materials and so on make most sources of fires. Seawater is usually the main extinguishing agent used on ships and high volumes of the water are hazardous to the vessel stability and subdivision. Therefore, in the paper, the main emphasis has been made on defining the impact of high located and flooded compartments on the ship stability safety. Results of calculations presented in the elaboration contain information regarding volumes of water in the compartment causing deterioration of the ship stability.

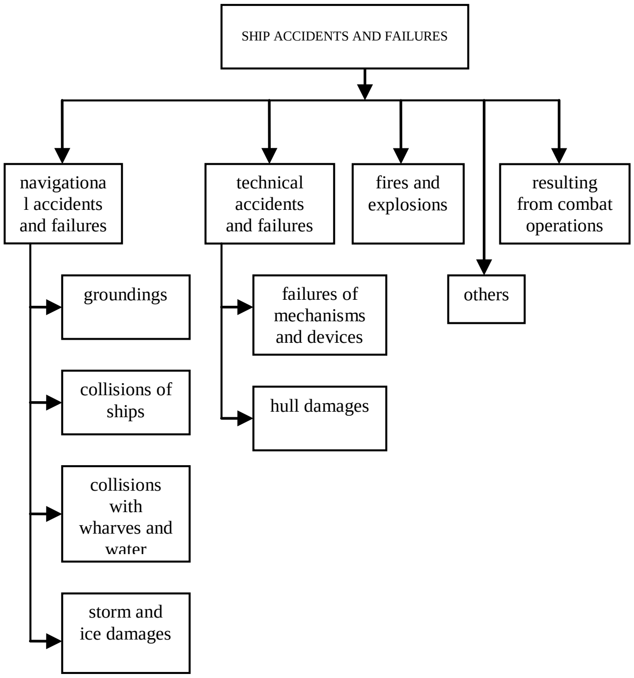

Fig. 1. Break-down of ship accidents and failures [4,6]

II. RESEARCH OBJECT CHARACTERISTICS

The training vessel selected for the tests is a flagship of the training and research ships’ wing of our fleet. The said boat is divided, with ten transverse watertight bulkheads, into 11 watertight compartments located on the frames: 3, 16, 25, 35, 50, 60, 71, 80, 91 and 101. Such division ensures maintenance of unsinkability when two neighbouring compartments have been flooded, excluding main engine room and adjoining compartment. Analysis of the damage stability after flooding high located compartments has been justified because the ship sails in different sea waters, so in various and dangerous weather conditions where the risk of damages is high. General characteristics of the vessel:

– main dimensions:

overall length:	L_c = 72,20 m,
length between perpendiculars:	$L_{pp} = L$ = 64,20 m,
maximal breath:	B_{max} = 12,00 m,
breath:	B = 11,60 m,
height:	H = 5,55 m.

The calculations have been made for load displacement and no icing.

Fig. 2. Picture of the training vessel [9]

These conditions are characterized by the following quantities:

- displacement: D = 1745,34 t,
- ordinate of the mass centre from the main plane: z_G=4,31 m,
- stern draft: T_R = 3,97 m,
- bow draft : T_D = 4,05 m,
- average draft: $T_{śr}$ = 4,01 m,
- trim: t = 0,08 m,
- metacentr height from the main plane: z_M = 5,44 m,
- metacentric height: GM = 1,13 m,
- speed: V =16,8 w
- coordinates of the mass centre:
  - x_G = 29,649 m from the after perpendicular,
  - y_G = -0,007 m from the plane of symmetry,
  - z_G = 4,314 m from the main plane [9].

III. DEFINING THE METACENTRIC HEIGHT AND THE RIGHTING LEVERS OF THE SHIP

Water broken into the vessel's hull and the flooded compartment or tank result in deeper draught of the ship, possible heel and trim as well as a change in her stability. The change may improve or aggravate operational conditions of the boat. In some case, lower stability may be serious enough to endanger safety of the ship and her crew as well as it may cause overturning of the vessel. To avoid accidents of such a kind, it is necessary to check stability of the damaged ship and apply appropriate remedial measures that would stop its lessening.

Flooding of high situated compartment or several compartments always results in aggravation of the vessel's stability. As a consequence, a heel or trim of the ship, change in the metacentric height and the righting levers may occur.

A vessel of standard displacement D for which a mass m is loaded in the point A (X, Y, Z) as in the Figure 3 [1,2,3] has been taken into consideration in the stability calculations.

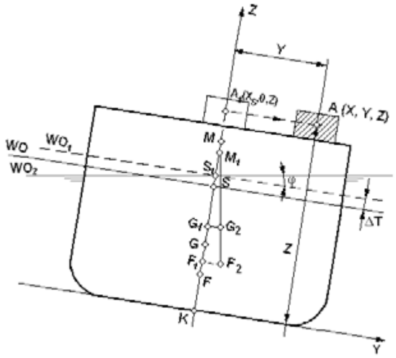

Fig. 3. Scheme of the ship situation after acceptance of the mass m in the point A [1,2,3]

At the beginning, acceptance of the mass was assumed so that to have its centre vertically above the centre of water-plane section's surface WO in the point A_1 (X_S, 0, Z). Then, it is possible to calculate [1,2,3]:

- the draught increase, as per the formula:

$$\Delta T = \frac{m}{\rho F_{WO}} \tag{1}$$

- the new transverse metacentric height, as per the formula:

$$\overline{G_1 M_1} = \overline{GM} + \frac{m}{D+m}\left(T + \frac{\Delta T}{2} - Z - \overline{GM}\right) \tag{2}$$

- the new longitudinal metacentric height, as per the formula:

$$\overline{G_1 M_{L1}} = \frac{m}{D+m}\overline{GM_L} \tag{3}$$

In the next step, the mass was moved from the imaginary position onto the place occupied in reality:

- towards the transverse direction by a distance of $e = Y - Y_1 = Y - 0 = Y$,

- towards the transverse direction by a distance of $l = X - X_S$.

The angle of heel of the ship has been calculated with the below formula:

$$tg\varphi = \frac{mY}{(D+m)\overline{G_1 M_1}} \tag{4}$$

and the trim of the vessel from:

$$tg\Psi = \frac{m(X - X_S)}{D\overline{GM_L}} \tag{5}$$

The new draughts of the bow and stern are defined from the following equations:

$$T_{d1} = T_d + \Delta T + \Delta T_d \tag{6}$$

$$T_{r1} = T_r + \Delta T + \Delta T_r \tag{7}$$

The final results are as follows:

$$T_{d1} = T_d + \frac{m}{\rho F_{WO}} + \left(\frac{L}{2} - X_S\right)\frac{m\left(X - X_S\right)}{D\overline{GM}_L} \quad (8)$$

$$T_{r1} = T_r + \frac{m}{\rho F_{WO}} + \left(-\frac{L}{2} - X_S\right)\frac{m\left(X - X_S\right)}{D\overline{GM}_L} \quad (9)$$

For large angles of heel (above 7°), the ship stability is defined based on the righting lever curves (Reed's curve). This curve allows determining dimensions of the righting lever for any angle of heel of the given ship, at invariable displacement and position of the mass centre.

Value of the righting lever $\overline{GH}$ is determined with the following formula applied [14]:

$$\overline{GH} = \overline{KC} - \overline{KL} \quad (10)$$

where:

$$\overline{KL} = Z_g \sin\varphi \quad (11)$$

Z_g – the mass centre height [m],
$\overline{KL}$ – the weight stability lever [m],
$\overline{KC}$ – the form stability lever [m].

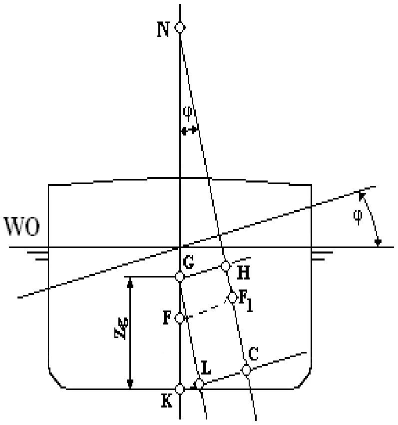

Fig. 4. Righting lever of the shape and mass [1]

The formula (10) may be presented in the following way:

$$\overline{GH} = \overline{KC} - Z_g \sin\varphi \quad (12)$$

For the determination of the righting lever for any angle of heel it is necessary to know the form stability lever that changes depending on the angle of heel. This value is read from the so-called Pantecaren graph, which is developed during the design phase of the ship.

Reed's curve which is a graph of righting levers provides information about the basic parameters of the stability of the ship, such as:

φ Gzmax – heeling angle at the maximum value of the righting lever occurs [deg],
GZmax – the maximum righting lever [m],
φr – the angle of vanishing stability [deg],
GM – the metacentric height [m].

IV. FREE SURFACE EFFECT

Presence of fluid free surface effect after partial flooding of compartment always results in reduction of the vessel's metacentric height. This decrease depends, among the others, on the shape and magnitude of this surface.

Receipt of liquid cargo on board of a ship, accompanied by occurrence of the free surface, has influence on change of position of the vessel mass centre and thus on the metacentric height $\overline{GM}$. Hence usage of, for instance, larger quantities of water for fire-fighting purposes on upper decks results in shifting the boat's mass centre up, and – if connected with occurrence of free surfaces – it may cause the loss of stability and overturning of the ship.

Impact of inertia moment derived from the free surface of the flooded compartment has been taken into account in the calculations of the metacentric height. It has been assumed that surface of the compartment under flooding is rectangular. The moments of inertia of the permanent constructional elements present in the compartment have been taken into consideration in calculations regarding the inertia moment of the entire body.

Determining the influence of the free surface effect of the liquid on the ship's stability the ship has been tilted by an angle φ. The layout of the partially filled liquid tank with a specific density ρ1 and volume v is shown in Figure 5. The liquid mass in the tank is calculated[1,2,3,10]:

$$m = \rho_1 * v \quad (13)$$

At any angle of heel the liquid in the tank is poured overboard and its surface is parallel to the sea water, assuming the position of WO1. The center of liquid mass, which in the upright position of the ship was at the point g, will move to the point g1 as a result of the change in shape of the fluid filled volume. The shape of the tank in the transverse section of the ship resembles a cuboid. The center of fluid mass g moves over the circle with the center at the point n. So the distance $\overline{gn}$ can be expressed by an equation[1,2,3,9]:

$$\overline{gn} = \frac{i_b}{v} \quad (14)$$

where:
i_b – interia moment of a free surface effect [m^4],
v – volume of the liquid inside the tank [m^3].

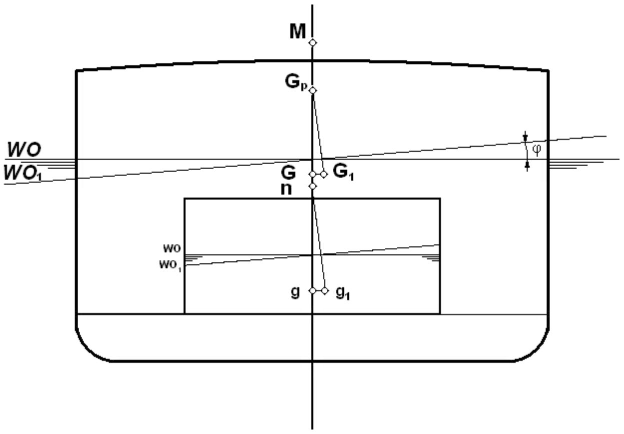

Fig. 5. Ship with free surface [1]

Because at low heel angles the direction of gravity of the liquid passes through the point n, so that the influence free surface effect of the liquid in the tank on the metacentric height of the ship will be identical to the effect that would induce the shift of the constant mass (equal to the weight of the liquid), whose center of gravity has gone from point g to point n. Actual movement the center mass of the fluid $\overline{gg_1}$ will cause a parallel displacement of the center of mass of the ship from point G to point G1, resulting in a reduction of the righting lever $\overline{GH}$ and thus a reduction in a ship stability. The direction of gravity force in the tilt will thus pass through G1, crossing the symmetry plane of the ship at point Gp. For small angles of heel, the Gp point is constant. The reduction of the metacentric height due to the movement of the center mass of the ship from point G to point G1 will be the same as the shift of center mass to point Gp. For this reason, this point is called the apparent medium of mass. The apparent displacement of the center mass of a ship from G to Gp is caused by the apparent center of mass displacement from g to point n. Therefore, the distance $\overline{GG_p}$ is calculated by the formula [1,2,3,11]:

$$\overline{GG_p} = \frac{\rho_1 * v}{\rho * V} * \overline{gn} = \frac{\rho_1 * v}{\rho * V} * \frac{i_b}{v} = \frac{\frac{\rho_1}{\rho} * i_b}{V} \tag{15}$$

Where:
ρ_1= density of the water inside the tank
ρ=density of the sea water
V=volume of ship displacement.

Since the arbitrary movement of the liquid mass is always vertically directed and directed upwards, it is accompanied by a decrease in the metacentric height [1,2,3]:

$$\overline{G_p M} = \overline{GM} - \overline{GG_p} = \overline{GM} - \frac{\frac{\rho_1}{\rho} * i_b}{V} \tag{16}$$

$\overline{G_p M}$ – reduced matacentric height

With more number of tanks not completely filled with liquids of different densities, the effect of free surfaces is summed up according to the formula:

$$\overline{G_p M} = \overline{GM} - \frac{\sum_{k=1}^{n} \frac{\rho_{pk}}{\rho} i_{bk}}{V} \tag{17}$$

where:
i_{bk} – subsequent interia moments of a free surface effect [m^4].

As can be seen from the above formulas, the presence of a free surface reduces the metacentric height of the ship, the reduction being dependent on the moments of inertia of the free surfaces.

Influence of the fluid free surface on the righting levers' curve (the Reed's curve) has been taken into account by implementing an allowance marked with an X symbol X[1,2,3].

$$X = \left[y_{G1}(\varphi)\cos\varphi + z_{G1}(\varphi)\sin\varphi\right] \tag{18}$$

where:
$y_{G1}(\varphi)$ and $Z_{G1}(\varphi)$ – constituents of shift of the vessel's mass centre, at the heel to the angle φ[m],

$$y_{G1}(\varphi) = \frac{\sum_{i=1}^{n} m_i \left[y_g(\varphi)\right]_i}{D} \tag{19}$$

$$z_{G1}(\varphi) = \frac{\sum_{i=1}^{n} m_i \left[z_g(\varphi)\right]_i}{D} \tag{20}$$

D – ship displacement together with liquid cargo [t],
m_i –mass of the liquid cargos in particular tanks [t],
$[y_g(\varphi)]_i$ and $[z_g(\varphi)]_i$ – constituents of shifts of the fluid mass centres in the flooded compartments at the heel to the angle φ [m] [10]. These parameters have been calculated with a used of an elaborated computer programme. This software is adapted to calculate stability parameters for a floating structure of rectangular shape.

After defining the allowance from the fluid free surface, the new GM is:

$$GM = G_1 M_1 - X \tag{21}$$

Based on the formula 21, the calculations and analyses of the vessel's metacentric height after flooding the ship compartment have been made.

V. RESULTS OF THE VESSEL STABILITY WITH A SHIP COMPARTMENT FLOODED

The calculations have been made for a compartment located at the height of 8,10 m from the main plane. This compartment, of the dimensions: width 8,67 m and length 36,78 m, is represented by a plane surface, after considering its equipment, equal 188,5 m^2. It was undergone flooding up to the water height H previously assumed.

The results of the righting levers calculations, with the free surface effect, for the considered water heights in the compartment, was taken into consideration. A course of changes of the righting levers' curve (the Reed's curve) versus the heel angle of the ship is presented in the Figure 6. The angles of steady heel of the ship, resulting from flooding of the vessel compartment under discussion, amount respectively: φ_{S1} = 12° for the water level in the compartment equal H = 1,0 m and φ_{S2} = 18° for H = 1,6 m. The metacentric heights for these cases display negative values.

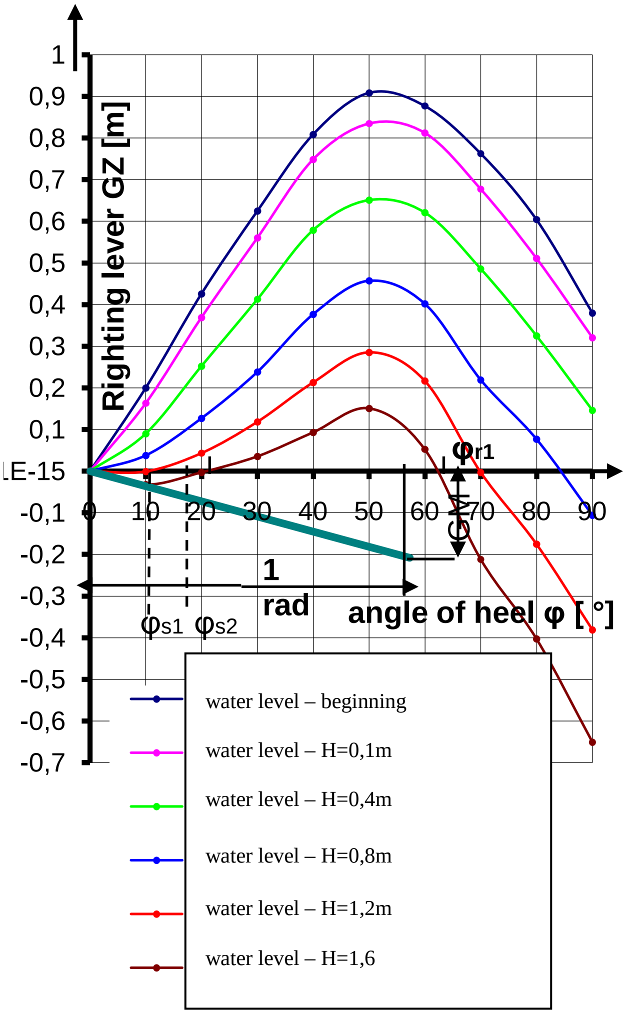

Fig. 6. Influence of the amount of water in the compartment on the Reed’s curve

For the amount of water in the compartments H = 1.6 m angle range of righting lever reduced from approx. φr = 100º to approx. φr = 60 °.

VI. CONCLUSION

As a result of analysis of the ship’s stability after flooding a high situated compartment provides the following conclusions:

Flooding of high located compartment results in:
- a reduction in a value of metacentric height,
- a reduction in a value of righting levers,
- a reduction in the angle range righting lever φr,
- an increase in a value of steady heel angle φ_S.

The analysis of changes in the stability of the ship shows, that the worst option is the simultaneous flooding of two compartments have to height H = 1.2 m. It causes a loss of initial stability of the ship. The recovery of stability followed by an inclination of the ship equal φs = 12 °.

In future work, I intend to analyze the stability of the ship after flooding several high located compartments.

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