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THE DYNAMIC FREE SURFACE EFFECT FOR DIFFERENT LOCATIONS OF PARTLY FILLED TANKS ON BOARD SHIPS

Key words

Sloshing, free surface effect, dynamic ship's stability, stability assessment, heeling moment.

Summary

The results of experimental research and numerical simulation of sloshing phenomenon are presented. The heeling moment due to the dynamic movement of the fluid in a partly filled ship's tank is computed. The dependence of heeling moment effects upon the locations of the tank in the hull is described.

Introduction – ship's stability assessment

The accuracy of ship's transverse stability assessment is the important factor in the vessel's exploitation process. The ship's loading condition of insufficient stability may induce the list, the strong heel and even the capsizing. Contrary to such a state, the excessive stability causes high values of mass forces acting on the cargo and the machinery due to the strong accelerations. Therefore, any scientific efforts towards better evaluation of ship stability are worthy to be undertaken.

1. Transverse stability of the ship

The stability of the ship is defined as a feature of the counteracting of the external heeling forces and moments, which should enable the efficient use of the ship [3]. The complete description of the stability may be obtained by solving the differential equations of ship's movement. The most convenient approach towards this task is to make the assumption of symmetrical mass distribution and steady values of moments of mass inertia [3]. The movement complex, referred to the centre of gravity G, has the form of six differential equations [3]. The solution of such general formulated movement equations is impossible at the present state of the art. By neglected coupling, for the sake of simplicity, the ship's rolling is usually analysed by the single degree-of-freedom system [12]. The governing differential equation of motion, as the result of equilibrium of moments, is [12]:

$$I\ddot{\varphi} + D(\dot{\varphi}) + R(\varphi) = M(t) \tag{1}$$

where:

I – moment of inertia of ship and added masses [kg·m^2];
D – damping moment [N·m];
R – restoring moment [N·m];
M – excitation moment [N·m];
φ – angle of heel [rad].

The resultant excitation moment *M(t)* consists of many components, as many influences swing the ship. The main components are waves and the wind. When the analysis of ship's rolling comprises the effects of water sloshing in partly filled tanks, then the moment of water-ship interaction has to be included as a component of *M(t)* in a/m formula (1).

Nevertheless, the simplified approach towards the ship's rolling, the solution of the equation (1) is still too complicated to be used in course of the on-board stability calculations made by the cargo officers during their everyday practice.

The vessel's stability calculation and evaluation, made on-board nowadays, is not based on the ship's movement equations but on the stability criteria published by the ship's classification societies. These criteria are mainly based on the A749(18) Resolution of International Maritime Organisation. The resolution and their later amendments are known as the Intact Stability Code [5].

The criteria regulate the shape of the righting arm curve, especially the minimum value of initial metacentric height, the value of maximum righting arm and the angle of this maximum, and the area under the righting arm curve calculated within the prescribed ranges of angles of heel. In addition, the weather criterion of the dynamic stability calculation is to ensure the sufficient stability of the ship to withstand the severe wind guests during rolling. However, the weather criterion is a very simple model of the ship's dynamic behaviour and the static stability curve is used. Nevertheless, the weather criterion is partly based on the model of heeling phenomenon, not only on the statistic data, while the rest of criteria are based only on the statistics of historical disasters [4].

The dynamic behaviour of the vessel at sea is greatly affected by the dynamics of moving masses existing on-board. The cargo securing procedures ensure avoiding loose cargo moving, but the moving liquids contained in partly filled tanks cannot be avoided at all. The modelling of the interaction between water sloshing inside the ship's tank and the tank's structure is very important with regard to the safety of shipping. The effects of liquid sloshing should be also taken into consideration in course of a vessel's sea-keeping prediction and transverse stability assessment.

According to the IMO regulations, the righting lever curve should be corrected for the effect of free surfaces of liquids in tanks. The correction may be done by any of three accepted methods as follows [5]:

1) A correction based on the actual moment of fluid transfer calculated for each angle of heel;
2) A correction based on the moment of inertia of tank's horizontal projection;
3) A correction based on the summation of M_{sf} values for all tanks taken into consideration, where the moment M_{sf} should be obtained from the simplified formula given in the Intact Stability Code [5].

All three methods of the free surface correction calculation consider the static approach towards the sloshing phenomenon only. They do not consider the location of the tank within the hull of the ship and the location of the rolling axis. The only advantage of pending compulsory corrections is the simplicity of the calculation.

2. Research into the sloshing phenomenon

Liquid sloshing phenomenon is the result of the partly filled tank motions. As the tank moves, it supplies energy to induce and sustain the fluid motion [1]. Both the liquid motion and its effects are called sloshing [1]. The interaction between the ship's and the tank's structure and the water sloshing inside the tank consists in the permanent transmission of the energy. As the ship rolls, the walls of the partly filled tank induce the movement of water. Then the water presses against the opposite wall of the tank and returns the energy to the ship, taking simultaneously the next portion, enabling the counter-direction movement. The mass and the energy are conserved within the cycle. The dynamic behaviour of the vessel at sea is greatly affected by the dynamics of the liquid with the free surface in tanks [7].

The experimental research into the sloshing phenomenon was performed in Ship Operation Department of Gdynia Maritime University. It enabled the measurement of the dynamic pressure distribution on the side-wall of the model tank and in its upper corner [8]. The experimental investigation on determining the pressure distribution due to sloshing required the generation of the sloshing phenomenon. After that, the dynamic pressure time-history in selected places were measured and recorded. To achieve this, a test apparatus was designed and built [8].

The amplitude of the tank's rotary motion during the model tests was assumed to be 18°, 30° and 40°. It reflects heavy seas conditions and enables making the conclusions for the worst possible condition at sea. The period of the oscillation varied from 2.6 s to 6.5 s. The dimensions of the model tank are the following: length – 1040 mm, width – 380 mm, depth – 505 mm. The assumption of the plane of the tank's oscillation and the neglected water viscosity resulted in the two-dimensional character of water flow inside the tank [6]. The detailed characteristic of the experimental research is described in [8].

The pressure distributions obtained by the experimental investigation were completed through the results of the numerical simulations. The computer program *Tank* used for the estimation of the dynamic pressure distribution due to sloshing was developed in The Polish Register of Shipping. The sloshing problem was described by a two-dimensional model. It was also assumed that the liquid is non-viscid, incompressible, and of constant density. Since the flow of the liquid was assumed irrotational, the potential theory was used to solve the sloshing problem [6].

The numerical simulation of the sloshing phenomenon was performed for the oscillation and the tank's geometry corresponding with the suitable geometric parameters of the experimental investigation. The height of water level varied from 30% to 90% of the maximum tank height. The program allows the computation of the time-history of dynamic pressures in ninety points around the tank's model. The control points are situated along vertical walls, the bottom and the tank's roof. The correctness of the simulation results was verified experimentally [11].

3. Heeling moment due to sloshing

The mathematical model of interaction between the water sloshing inside the ship's tank and the hull's structure was prepared for a rectangular tank. It corresponds with the shape of the tank used during the experimental research and the numerical simulations, described in paragraph 2. An example of the tank's location and the forces due to sloshing is shown in the Fig. 1. It is assumed that the rolling motions of the ship and the tank take place about the rolling axis, which is perpendicular to the plane of the Fig. 1 and contains the point *O*. The forces F_1 to F_6 are local, and they act on both side-walls of the tank, its roof and the bottom, as shown in the Fig. 1. The local value of the moment of force due to sloshing is the product of multiplying the force by the lever about the rolling axis. The lever can be defined as the distance between the line of force acting and the rolling axis (point *O*).

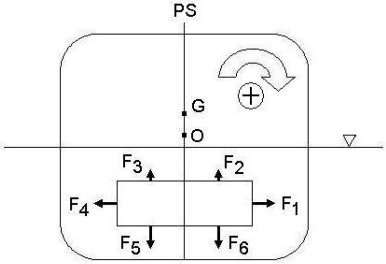

Fig. 1. The arrangement of forces affecting tank's structure

The locations of the side-walls of the tank and its roof and bottom are fixed by the standard ship's vertical and transverse co-ordinates. It is assumed that the bottom of the tank is situated at the height z_{min} and its roof at the height z_{max}. The port side-wall of the tank has the transverse co-ordinate y_{min} and the starboard side-wall y_{max}. The symmetry plain has the *y* co-ordinate equal zero. Taking all the assumptions into consideration, the total values of force moments on the individual panels numbered 1 to 6 (see Fig. 1) can be calculated as the following integrals, and the total value of heeling moment due to sloshing inside the ship's tank is calculated as the sum [10]:

$$
\begin{aligned}
M_1 &= -\int_{z_{\min}}^{z_{\max}} p_{1(z)} \cdot r_{(z)} \cdot l \cdot dz & M_4 &= \int_{z_{\min}}^{z_{\max}} p_{4(z)} \cdot r_{(z)} \cdot l \cdot dz \\
M_2 &= -\int_{0}^{y_{\max}} p_{2(y)} \cdot r_{(y)} \cdot l \cdot dy & M_5 &= -\int_{y_{\min}}^{0} p_{5(y)} \cdot r_{(y)} \cdot l \cdot dy \qquad M = \sum_{i=1}^{6} M_i \\
M_3 &= \int_{y_{\min}}^{0} p_{3(y)} \cdot r_{(y)} \cdot l \cdot dy & M_6 &= \int_{0}^{y_{\max}} p_{6(y)} \cdot r_{(y)} \cdot l \cdot dy
\end{aligned}
\tag{2}
$$

where:

M_i – force moment on *i*-numbered tank's wall [N·m];
M – total heeling moment due to sloshing [N·m];
p_i – local pressure on *i*-numbered tank's panel [Pa];
r – lever of force moment [m];
l – length of the tank (along *x*-dimension) [m];
y – transverse co-ordinate [m];
z – vertical co-ordinate [m].

The resultant moment obtained from formula (2) represents one time-step only. The calculation of heeling moment should be performed for at least one period of roll. Thus, the pressures p_1 to p_6 have to be investigated for at least one period of the ship's roll as well.

The heeling moment due to sloshing was calculated based on the dynamic pressure time-history from formula (2). The computations of time-domain heeling moment due to sloshing were performed for five locations of the rolling axis. The ratio of elevation z_o of the rolling axis above the tank's centre to the model tank's breadth b, was taken from $z_o/b = -0.7$ to $z_o/b = 0.7$.

The example of the resultant heeling moment calculated for rolling amplitude 40°, water level 60% and the rolling axis situated above the tank ($z_o/b = 0.7$) is shown in the Fig. 2. The heeling moment was time-domain calculated, but it is drawn as a function of the angle of heel.

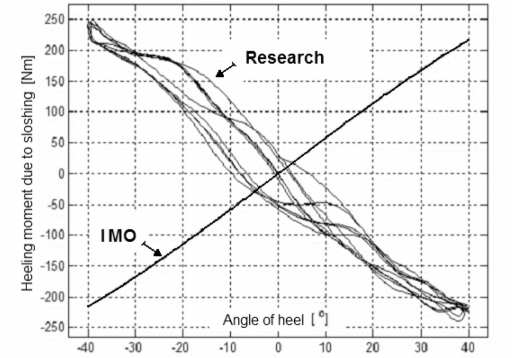

Fig. 2. Heeling moment due to sloshing for the tank situated beneath the rolling axis

The analysis of heeling moment graphs, obtained for different locations of the partly filled tank, reveals the considerable dependence between them. The heeling moment values M, computed for the maximum researched angle of heel equal 40° were compared to the value of heeling moment M_{IMO} obtained up to the IMO Intact Stability Code recommendation. The computations were made for different arrangement of the rolling axis and the partly filled tank (Fig. 3).

The curves in Fig. 3 were obtained for the T/T_w ratio from 1.9 to 4.8, where T is the ship's rolling period and T_w is the natural period of water movement inside the tank. The scope of T/T_w ratios reflects the wide variety of characteristics they can have place onboard ships at different loading conditions [9]. The value of dynamic heeling moment M due to sloshing at the investigated angle of heel 40°, referred to the roll axis location, has characteristics very close to linear. When the tank is 60% full, the linear correlation coefficient reaches the values from $R^2 = 0.959$ for $T/T_w = 1.9$ to $R^2 = 0.998$ for $T/T_w = 4.8$. The value of heeling moment M_{IMO} obtained with regard to the IMO Intact Stability Code recommendation does not depend on the arrangement of the partly filled tank and the axis of roll.

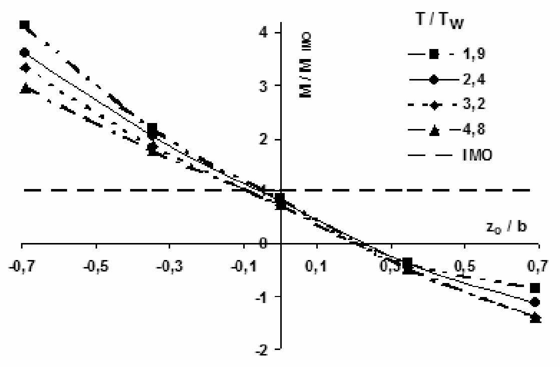

Fig. 3. Heeling moment values due to sloshing of water at the angle of heel of 40 degrees for different arrangements of the partly filled tank in relation to the axis of roll

Conclusions

The movement of liquids on ships within partly filled tanks affects her stability; therefore, it is considered in he course of the stability assessment procedure up to the IMO recommendations. The research presented in this paper indicates that the very simplified methods accepted by IMO cannot be used for the purposes of dynamic stability assessment at the satisfying level of accuracy as per the modern requirements of ship exploitation.

The IMO-recommended computation of heeling moment due to liquid transfer in tanks is inadequate, and it is even opposite to the angle-of-heel domain characteristics of the heeling moment due to sloshing for some cases (Fig. 2). The results of this study indicate clearly that the location of the partly filled tank has an important influence on the heeling moment characteristics. However, this location is not considered in the Intact Stability Code recommendations [5]. The value of the heeling moment due to sloshing obtained for the maximum researched angle of heel, depends strongly on the location of the tank (Fig. 3), in reverse to the free surface correction used on-board so far. The suggestion is to continue the research into the dynamic aspect of ship's stability assessment comprising the influence of the sloshing phenomenon. As long as the prescription approach towards the stability criteria will be in force, the dynamic free surface correction could be used. It should consider the location of partly filled tanks in relation to the axis of roll. This would be a step ahead towards an increase in the accuracy of the ship's stability estimation, which should allow an improvement in the safety of the ship and the economic aspect of her exploitation.

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Dynamiczny efekt występowania swobodnych powierzchni cieczy w zależności od lokalizacji na statku zbiorników częściowo zapełnionych

Słowa kluczowe

Swobodne powierzchnie cieczy, stateczność dynamiczna statku, ocena stateczności, moment przechylajacy, sloshing.

Streszczenie

W artykule przedstawiono wyniki badań eksperymentalnych i symulacji numerycznych w zakresie przebiegu momentu przechylającego statek wskutek ruchu cieczy w niepełnych zbiornikach. Uwagę zwrócono na wpływ położenia niepełnego zbiornika względem osi kołysań bocznych statku.