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Dynamic Component of Ship's Heeling Moment due to Sloshing vs. IMO IS-Code Recommendations

P. Krata
Gdynia Maritime University, Gdynia, Poland

ABSTRACT: The comparative study of the dynamic component of heeling moment due to sloshing in ships' partly filled tanks is presented in the paper. The characteristics of heeling moment are obtained in the course of experimental tests and numerical simulations. The heeling moment is decomposed and the research is focused on the dynamic component resulting from liquid movement. The results of the research are compared to the computations performed in accordance with the IMO IS-Code recommendations. The need for amending of the intact ship stability assessment procedure is suggested.

1 INTRODUCTION

1.1 *Sloshing phenomenon as one of factors influencing safety of a vessel at seaway*

The dynamic behavior of a vessel at the sea is greatly affected by the dynamics of moving masses existing onboard. The cargo securing procedures ensure avoiding moving of a loose cargo, but the liquids contained in partly filled tanks cannot be avoided at all. Regardless the strength calculation the effects of sloshing should be also taken into consideration in the course of vessel's seakeeping prediction and her transverse stability assessment.

Liquid sloshing phenomenon is a result of partly filled tank motions. As a tank moves, it supplies the energy to induce and sustain the fluid motion (Akyildiz & Unal 2005). Both the liquid motion and its effects are called sloshing. The interaction between the ship's and tank's structure and the water sloshing inside the tank consists in the constant transmission of energy. As the ship rolls, the walls of a partly filled tank induce the movement of water.

In such an attitude ship's seakeeping behavior which comprises the notion of her stability is one of the researched key issues leading to the increase in understanding of the safety qualifying factors.

1.2 *Intact ship 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 a list, a strong heel and even a capsizing. Contrary to such state, the excessive stability causes high values of mass forces acting on cargoes and machineries due to a strong accelerations. Therefore, any scientific efforts towards the better ship's stability evaluation are worthy to be undertaken. The influence of sloshing phenomenon on the ship's stability is one of the issues to be considered.

The vessel's stability calculation and evaluation, made on-board nowadays, is based on the stability criteria published by the ship's classification societies. These criteria are mainly based on the A749(18) Resolution of International Maritime Organization. The resolution and their later amendments are known as the Intact Stability Code.

The criteria qualify the shape of the righting arm curve. In addition, the weather criterion is to ensure the sufficient stability of the ship to withstand the severe wind guests during rolling. Although the weather criterion is a very simple model of dynamic ship's behavior, the static stability curve is used. Anyway, the weather criterion is the only, which is partly based on the model of heeling phenomenon not only on the statistic data, while the rest of criteria are based on the statistics of historical disasters only (Francescutto 2002).

According to the IMO recommendations 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 (IMO 2002):

– correction based on the actual moment of fluid transfer calculated for each angle of heel;

- correction based on the moment of inertia of tank's horizontal projection (simple pendulum model);
- correction obtained form the simplified formula given in the Intact Stability Code.

All of the three mentioned above methods of free surface correction calculation consider the static attitude towards the sloshing phenomenon only. They also do not consider the localization of the tank within the hull of the ship and the localization of the rolling axis. The only advantage of current compulsory corrections is the simplicity of their calculation.

2 RESEARCH INTO THE PRESSURE DISTRIBUTION IN A MOVING TANK

2.1 *Research assumptions*

The scheme of undertaken research comprises physical model tests and numerical simulations as well. The admitted assumptions refer to both and they describe dimensions of the model tank, its movement geometry and characteristics, tank's filling level.

The oscillating movement, which induces the sloshing phenomenon, is described fair enough by the harmonic function. The research into the pressure distribution due to the sloshing was performed for a variety of the external excitation parameters. The period of the oscillation varied from T=2,6 s to T=6,5 s. The lever *os*, as the distance between the center of the tank and the rotary motion axis, was changed from *os*=-0,718 m to *os*=0,718 m. The positive value of *os* describes the tank's localization beneath the rolling axis and the negative value of *os* describes the tank's localization above it. The amplitude of tank's rotary motion during the model tests and numerical simulations, assumed to be 40º. It reflects the heavy seas conditions and enables to make the conclusions for worst possible condition at the sea. The tank filling level assumed to be 30%, 60% and 90%.

2.2 *Experimental investigation*

The experimental research into the sloshing phenomenon was performed in Ship Operation Department of Gdynia Maritime University. It enabled to measure the dynamic pressure distribution on the sidewall of the model tank and in its upper corner (Krata 2006). The experimental investigation on the pressure distribution due to sloshing required the arousing of the sloshing phenomenon. After that, the dynamic pressure time history in selected spots were measured and recorded. To achieve this, the test apparatus was designed and built (Krata 2006).

The main part of the apparatus is the tank. It is equipped with pressure transducers and an inclinometer. The tank is forced to oscillating movement that excites the water movement inside it. The dimensions of the model tank are: breath – 1,040 m, length – 0,380 m, depth – 0,505 m.

The assumption of plane tank's oscillation and the neglected water viscosity, results the two-dimensional character of water flow inside the tank (Warmowska, Jankowski 2005). It allowed equipping the tank with one set of pressure transducers, fixed in the middle line of the tank. The pressure transducers were installed evenly alongside the vertical wall of the tank and in the roof of the tank close to the upper corner. The experimental setup is shown in Figure 1. The schematic plan of the apparatus is shown in Figure 2.

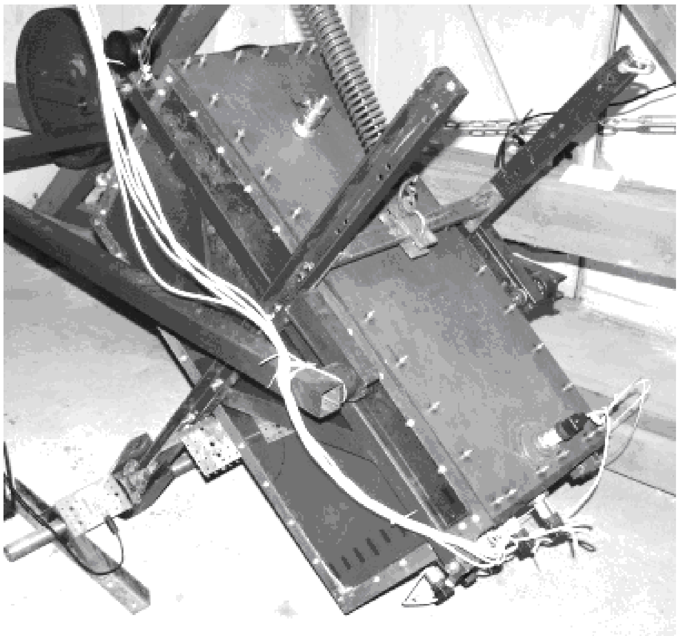

Figure 1. The experimental setup (the tank placed above the shaft – one of possible cases)

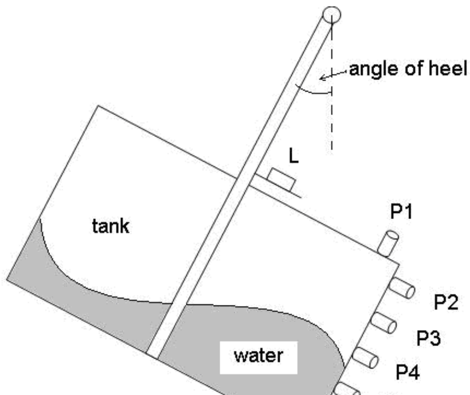

Figure 2. The scheme of the testing apparatus and the localization of dynamic pressure gauges named P1 to P6 and the inclinometer L

The location of pressure transducers installed in the front wall of the tank and in its upper corner is specified in the Table 1. Any further details are described in (Krata 2006).

Table 1. Geometry of pressure gauges installation

No. of pressure gauge	Elevation above tank's bottom [mm]	Horizontal distance from the tank's wall [mm]	Vertical distance between gauges [mm]
P1	505	60	70
P2	435	0	95
P3	340	0	95
P4	245	0	95
P5	150	0	95
P6	55	0	

The analog signals received from the sensors were sampled and transformed into discrete digital signals by the 12-bit A/D card and then they were recorded. The maximum working frequency of the measuring device was 1000 Hz. Thus, the aliasing distortions of the measured signal were avoided, because the measuring instruments were much faster than the required Nyquist rate for the sloshing phenomenon.

The further digital signal processing was carried out. The main operation was low pass filtering for high frequency noise reduction. The filtering enabled to decompose the recorded digital signal and emerged the non-impulsive dynamic pressure component.

2.3 *Numerical simulation*

The pressure distributions obtained in the course of the experimental investigation were completed by the results of numerical simulations. The simulations of sloshing phenomenon were performed by the computer program "Tank" by M. Warmowska, used for the estimation of the dynamic pressure distribution. The sloshing problem was described by two-dimensional model. It was also assumed that the liquid is non-viscid, incompressible, of constant density. As the flow of the liquid assumed to be irrotational, the potential theory was used to solve the sloshing problem (Jankowski, Warmowska 1997).

The numerical simulation of sloshing phenomenon was performed for the oscillation and tank's geometry corresponding with the suitable geometric parameters of the experimental investigation. The program allows computing 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 (Krata 2006).

3 HEELING MOMENT DUE TO SLOSHING

3.1 *Computation of heeling moment*

The pressure distribution on the walls of the tank was obtained in the course of the experimental tests and numerical simulation. The results of the research enable to compute a heeling moment due to the liquid's sloshing. The heeling moment $\boldsymbol{M}$ was calculated according to the following formula:

$$\boldsymbol{M} = \int_S \boldsymbol{r} \times \boldsymbol{n} \cdot p \, ds \qquad (1)$$

where: S – the surface of the tank's walls; $\boldsymbol{r}$ – the position vector of the considered point on the tank's wall; $\boldsymbol{n}$ – the normal vector; p – the local pressure on the tank's wall.

Due to the two-dimensional character of the considered flow in the tank, the heeling moment is a vector of a direction perpendicular to the plane of the tank's movement. As the transverse stability of a ship is assumed to be considered, the heeling moment has one spatial component only, as follows:

$$\boldsymbol{M} = \lfloor M_x, M_y, M_z \rfloor = [M_x, \quad 0, \quad 0] \qquad (2)$$

where: M_x, M_y, M_z – spatial components of $\boldsymbol{M}$ vector, determined about the x, y and z axis in the reference system fixed to the vessel.

As the direction of the heeling moment is fixed and steady in the time domain, the heeling moment due to sloshing may be described by the value of M_x spatial component. The resultant moment obtained from the formula (1) represents one time-step only. The computation of heeling moment should be performed for at least one period of roll. Thus, the pressures have to be investigated for at least one period of ship's roll as well, but actually they were obtained for the longer time comprising few rolling periods. The example of the heeling moment history graph is presented in Figure 3.

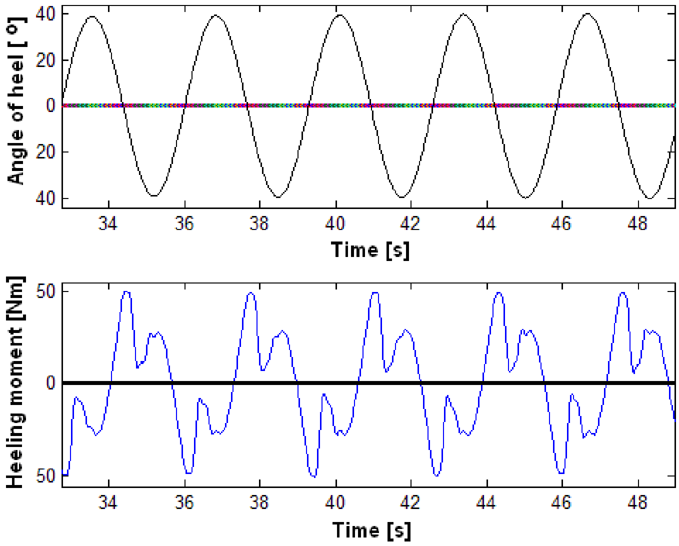

Figure 3. The time-domain presentation of the computed heeling moment due to sloshing

The time domain presentation of the computation results can be useful when the ship's rolling is to be computed on the basis of movement equations. In such case, the heeling moment due to sloshing is one of the components of total heeling moment rocking a vessel at seaway.

3.2 *Linearization*

The time-domain manner of presentation of the heeling moment due to sloshing which is shown in Figure 3 as a moment history graph is not convenient in respect of traditional ship's stability assessment (Krata 2008). Such stability assessment is not based on the movement equations, but on the static stability curve (IMO 2002). The curve presents the righting arm *GZ* in the angle of heel domain and the righting arm is reduced by the statically calculated free surface correction. Therefore, the most convenient way to present the results of the heeling moment calculation due to the sloshing of liquid in a partly filled tank is the angle of heel domain graph.

The interpretation of the results of heeling moment computation is much more convenient in angle of heel domain. The main disadvantage of such presentation is the hysteresis, which is the effect of wave type phenomena taking place inside the moving tank. The disadvantage can be removed by the linearization process (Krata 2008).

As the main task of the research is more reliable stability assessment with regard to the sloshing phenomenon, the linearization should refer to the ship's stability criteria, especially the weather criterion. The area under the *GZ* curve is qualified within the weather criterion, which represents the work of heeling moment due to wind guests when a ship rolls, so the linearization of the researched heeling moment should be based on the work of the moment as well. The linearization method applied to the heeling moment due to the sloshing of liquids is based on the formula:

$$\int_0^{\varphi_{40}} M_{(\varphi)} \cdot d\varphi + \int_{\varphi_{40}}^{0} M_{(\varphi)} \cdot d\varphi = 2\int_0^{\varphi_{40}} M_l \cdot d\varphi \qquad (3)$$

where: M – heeling moment due to sloshing; M_l – resultant linear heeling moment due to sloshing; φ – angle of ship's heel; φ_{40} –angle of heel equal 40° (given in radians).

The formula (3) ensures equality of works done by the researched heeling moment and linear heeling moment due to sloshing. Thus, the method may be called the equivalent work method. The example of linear heeling moment due to sloshing is presented in Figure 4.

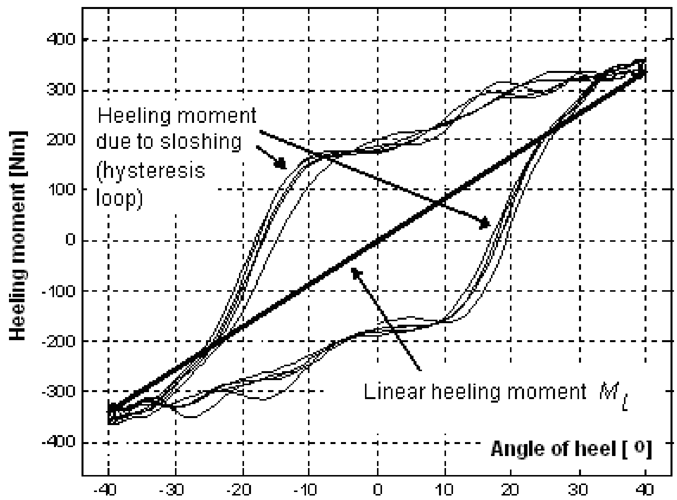

Figure 4. The example of the linear heeling moment, for the filling level 30% and *os*=-0,718 m.

The linear function of heeling moment can be determined by the fixing of two in-line points having the coordinates (φ, M). One of them is the point (0, 0) and the second one the point (40°, M_{l40}). Therefore, the complete description of the linear heeling moment obtained in the course of the research may be done by one scalar only, which is convenient for any further analysis.

3.3 *Extraction of dynamical component of the heeling moment due to liquid sloshing*

The moment M heeling a ship in consequence of liquid existence carried in any partly filled tank, may be decomposed into two components. One of them is the moment M_m of liquid weight and the second is the heeling moment M_{RB} due to the movement of fluid inside the tank. The heeling moment due to liquid sloshing in vessel's tanks can be described in every time-step by the formula:

$$M = M_m + M_{RB} \quad (4)$$

where: M_m – heeling moment due to the weight of "frozen" liquid in tank; M_{RB} – heeling moment due to the movement of fluid inside partly filled tanks.

The simple sum of moment components analogous to the formula (4) was applied to the linear heeling moment M_l calculated according to the formula (3) for all considered cases. Thus, the component M_{RB} of the heeling moment due to sloshing abstracts the static effect of liquid weight in ship's tanks. Such abstraction capacitates to bear comparison of the performed research results with the quasi-static heeling moment computed according IMO IS-Code recommendations.

4 RESULTS OF THE RESEARCH

4.1 *Comparison of the research results and IMO IS-Code recommended computation*

The research is focused on the comparative analysis of the heeling moment components arising from the liquid movement inside ship's partly filled tanks. One of them is obtained in the course of the research and it reflects the dynamic attitude towards the sloshing phenomenon. The other is calculated according the IMO IS-Code recommendations and it is of quasi-static type. The computation formulas resulted from IS-Code prescriptions.

The heeling moment M_{IMO} due to liquid's existence inside any partly filled tank may be decomposed into two components according to the formula:

$$M_{IMO} = M_m + M_{RIMO} \quad (5)$$

where: M_m – heeling moment due to the weight of "frozen" liquid in tank; M_{IMO} – heeling moment of the transfer of the liquid's center of gravity.

The moment M_m is taken into consideration in course of the calculation of the ship's center of gravity and it assumes the liquid to be "frozen" at the angle of heel equal 0°. It is important to notice, that the M_m component is equal in formulas (4) and (5). Therefore, the remaining components M_{RB} and M_{IMO} of the heeling moment may be compared. The component M_{IMO} of the heeling moment can be calculated at any of the three accepted method. The simple pendulum model is considered as safest for the ship therefore the free surface correction based on the moment of inertia of tank's horizontal projection was applied in the course of the further comparison.

The quasi-static component M_{IMO} of heeling moment is a function of sine of the angle of heel. Anyway, it could be compared to the researched linear component of the heeling moment due to sloshing for the range of angles of heel where the sine function may be approximate by linear function fair enough. The reasonable range of such linear approximation is about 40°, which shows Figure 5.

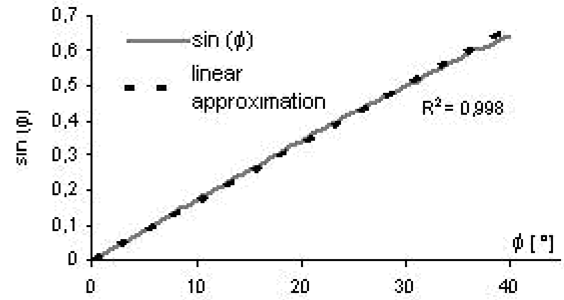

Figure 5. Linear approximation of sine function

As the sine function is almost linear up to the angel of heel 40°, the components M_{RB} and M_{IMO} of the heeling moment may be compared. They both have the zero values for the zero angle of heel, so their comparison may be done as the comparison of their values for the angle of heel equal 40°. Thus, the values M_{RB40} and M_{IMO40} are analyzed instead of the moment graphs. The comparison of the M_{RB40} values obtained in the course of the research and the M_{IMO40} computed according to the IMO recommendations is shown in Figure 6.

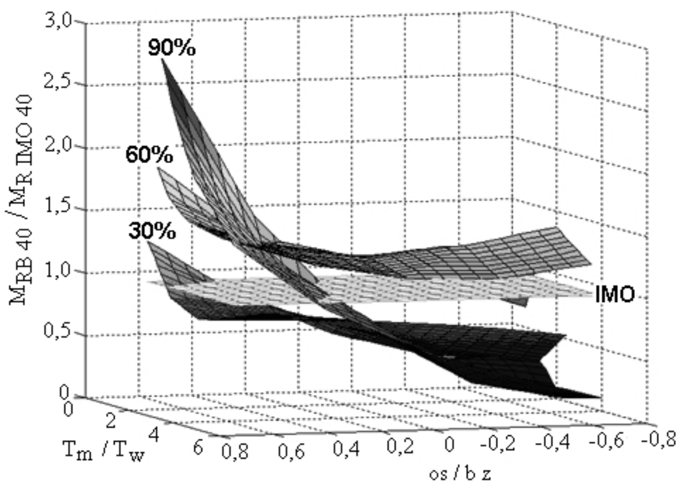

Figure 6. Non-dimensional component of heeling moment due to liquid movement in partly filled tanks.

The graphs showing analyzed values of the component of heeling moments are prepared as non-dimensional referred to the value M_{IMO40} of static free surface correction. The excitation period T is referred to the first harmonic natural sloshing period of a liquid in model tank T_w. The scope of T/T_w ratios reflects the wide variety of characteristics they can take place on board of ships at different loading conditions. The distance *os* between the center of the moving tank and the rotary motion axis is referred to the breath of the tank b_z. The three graphs marked 30%, 60% and 90% are plotted for the corresponding three levels of tank filling. The reference surface marked IMO is plotted for M_{IMO40} values calculated according the IMO IS-Code requirements.

4.2 *Analysis of the obtained results*

The quasi-static heeling moment component represented by the free surface correction described in IMO IS-Code depends on the shape of a partly filled tank only. Presented results of the research prove the significant influence of other factors. One of the most important is the localization of the tank referred to the vessel's rolling axis os/b_z. The excitation period referred to the first harmonic natural sloshing period of a liquid in model tank seems to be less important. The lowest investigated values of T/T_w ratios can occur for very short ship's rolling period typical for extremely stable ships. In any other cases, the T/T_w ratio does not play the important role.

The graph presented in Figure 6 enables the identification of potential danger to a vessel caused by the movement of liquid in partly filled tanks. Any value of analyzed heeling moment component higher than the reference level IMO should be considered as potentially perilous to a vessel because her transverse stability can be worse than calculated according to IS-Code recommendations.

The surface plotted for 30% of tank filling demonstrates that such a low level of filling does not need to be considered as risky one. The influence of liquid sloshing is weaker than that taken into account in the course of standard stability assessment. The only trespass of the reference IMO level is noticed for the shortest rolling period, which can take place in the case of large GM only.

The surface plotted for 60% tank filling level reveals the fair conformability of the research results and IS-Code recommendations for partly filled tanks situated above the ship's rolling axis and the considerable transgression for tanks placed below the rolling axis. The potentially dangerous underestimation of the liquid sloshing influence on the ship's transverse stability occurs for all researched rolling periods.

The surface plotted for 90% of tank filling prove the potentially perilous situation, which can take place for high levels of tank filling. The effect of liquid sloshing is slightly overrated for partly filled tanks situated above the ship's rolling axis when computed according to IS-Code. Such an effect may be considerably underestimated for tanks sited below the rolling axis, for instance double bottom tanks.

5 CONCLUSIONS

The movement of liquids in partly filled ship's tanks affects her stability and therefore it is considered in course of the stability assessment procedure according to the IMO recommendations. The results of the research presented in the paper points that the very simplified methods recommended by IMO could be improved and reach better accuracy to meet the modern requirements of ship's exploitation.

The presented comparative analysis of the components of heeling moment reveals some weaknesses of IS-Code. The use of current IS-Code recommendations may lead to considerable underestimation of free surface effect. This results from the quasi-static attitude towards the sloshing phenomenon. The analysis proves that the dynamic movement of liquids in partly filled tanks should not be neglected. The results of the research can contribute to the further investigation of the new formula of free surface correction comprising the dynamics of sloshing phenomenon.

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