DYNAMIC HEELING MOMENT DUE TO LIQUID SLOSHING IN A RECTANGULAR TANK OF DIFFERENT DIMENSIONS AND ELEVATION IN SHIP'S HULL

DYNAMICZNY MOMENT PRZECHYLAJĄCY OD SWOBODNYCH POWIERZCHNI CIECZY W PROSTOKĄTNYM ZBIORNIKU OKRĘTOWYM O RÓŻNYCH WYMIARACH I LOKALIZACJI PIONOWEJ

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Abstract: Liquid sloshing phenomenon taking place in partly filled ships' tanks directly affects the stability of a vessel and her safety on seaway, however, only static calculations are carried out onboard ships nowadays. The presented investigation is focused on dynamic approach towards liquid motion onboard ships. The set of numerical simulations of liquid sloshing taking place in moving tanks is carried out in terms of tank's dimensions and its elevation within ship's hull. A number of characteristics of the heeling moment due to liquid sloshing is obtained and analyzed.

Keywords: liquid sloshing in ship's tank, free surface effect, dynamic stability of ships, safety of navigation

Streszczenie: Zjawisko sloshing'u zachodzące w niepełnych zbiornikach okrętowych bezpośrednio wpływa na stateczność statku i związane z nią bezpieczeństwo żeglugi. Jednakże współcześnie na statkach uwzględniany jest wyłącznie statyczny moment od swobodnych powierzchni cieczy w zbiornikach. Przeprowadzone badania nakierowane są na określenie wpływu wymiarów i pionowego położenia zbiorników na dynamiczny moment przechylający. Analizowane charakterystyki momentu określono na podstawie wykonanych symulacji numerycznych badanego zjawiska.

Słowa kluczowe: zjawisko sloshing'u w zbiornikach okrętowych, swobodne powierzchnie cieczy, stateczność dynamiczna statku, bezpieczeństwo żeglugi

1. Introduction

The economical significance of marine transportation is still growing, even in the age of world's crisis, due to the cost reduction efforts among enterprises and resulting from them relocation of global production areas. The main commonly discussed features of maritime transport are usually its safety and effectiveness. Among them the ships safety issues are crucial from the operational point of view and they can be considered as one of the most prospective technical affairs. One of the most critical features of seagoing ships related to her safety is stability influencing ship's overall seakeeping performance.

The notion "stability" is used to describe the tendency of a ship to return back to her equilibrium when she is inclined from an upright position [6]. Since the initial position of a ship is not always upright one, the more practical definition states that the stability is a feature enabling to perform, when remaining in determined position, the task she is constructed for [6]. Both definitions are complementary and they lead to point out that the stability of a ship is an element of her operational safety qualifying factors. The next term strictly related to the subject are capsizing and loss of stability being a stability accident and defined as exceeding the amplitude of rolling or angle of heel at which operating or handling of a ship is impossible [6].

Stability against capsizing and excessive heeling is one of the most fundamental requirements considered by naval architects when designing ships and by their operators in the course of sailing and cargo handling [2]. The stability of a vessel belongs to operational characteristics enabling cost effective and safe operation [2]. The stability of an oscillating system is estimated by the ability of the system to absorb and dissipate the kinetic energy transmitted to the system by external disturbances (waves, wind etc.). Thus, the limit of range of ship stable oscillations shows that a possibility of capsizing exists if external disturbances are too large for the particular ship in her loading contemporary condition [6]. The relative danger due to the occurrence of such disturbances could be estimated with the use of reserve stability concept. From the point of view of the energy balance the reserve stability is proportional to the difference between the limiting value of work of the righting moment and the total kinetic energy of rolling under the influence of external loads [6].

In the light of contemporary ship stability related concepts, the accuracy of ship's transverse stability assessment is an important problem in vessels' operation process. The ship loading condition of insufficient stability may induce a list, a strong heel and even her capsizing. Contrary to such state, the excessive stability causes high values of mass forces acting on cargoes and machineries due to strong accelerations.

2. Liquid Sloshing Phenomenon

Liquid sloshing phenomenon taking place in partly filled ship's tanks contribute to the overall stability performance of a vessel among many other phenomena. According to the referred energy balance approach, the work of ship's righting moment needs to be compared to the total rolling energy including all its significant elements. One of such element is the moment due to liquid sloshing in tanks. As a tank moves, it supplies energy to induce and sustain a fluid motion. Under external large amplitude excitations or an excitation near the natural frequency of sloshing, the liquid inside tank is in violent oscillations which is of great practical importance to the safety of the liquid transport [10]. Both the liquid motion and its effects are called sloshing. The interaction between ship's tank structure and water sloshing inside the tank consists in the constant transmission of energy [1].

The seagoing vessel's stability calculation and evaluation made onboard nowadays is based on the prescriptive 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 [5].

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 gusts during rolling [6]. 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 [4].

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 two accepted methods [5]:

- 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).

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 location of the tank within the hull of the ship and the localization of the rolling axis. However, the main advantage of currently applied compulsory corrections is the simplicity of their calculation.

Regardless the explicit computational formula for free surface correction, the liquid surface is always assumed flat and depends only on an angle of ship's heel not

time. The idea is presented in the sketch (Fig. 1 - left). Since the actual shape of free surface of liquid in a moving partly filled tank is time-variable and non-linear (Fig. 1 – right).

Fig. 1. Flat surface of waterline and liquid's free surface in partly filled tank (left) and actual shape of the free surface in a model tank during an experiment (right)

The photo presented in the figure 1 was taken during an experimental research carried out in the Faculty of Navigation at the Gdynia Maritime University. The main purposes of the experiment is to verify the results of numerical simulations of sloshing phenomenon performed with the use of CFD technique and to systematically observe the shape of the free surface during the consecutive oscillations of the model tank.

3. Ship and Tank Geometry Applied in the Course of the Research

The characteristics of heeling moment due to liquid sloshing depend on a variety of parameters, for instance tank's geometry, its filling level, location of a tank within a hull of a ship, rolling period and others. The influence of ship rolling period is the main subject of the paper, thus, the research is focused on this matter. However, a number of features needs to be taken into account.

The pre-study carried out in the course of the research enabled the classification of typical shapes and dimensions ship tanks [9]. The double bottom tanks belongs to standard arrangement of all seagoing ships, while the side tanks and wing tanks are typical for same types only. The previous authors' researches reveals that liquid sloshing dynamics in ships side tanks can be neglected actually. The natural period of liquid sloshing is short enough to justify the quasi static calculation of the free surface effect. This approach is well known and routinely applied in the course of the stability assessment [5]. A liquid contained in partly filled side tanks remains actually horizontal and flat within the all ship rolling cycle, which is shown in Fig. 2. The wider tanks, for instance double bottom tanks, need to be the subject to examine in terms of possible sloshing characteristics.

Fig. 2. The surface of liquid sloshing in partly filled high side tanks: disturbed and flat free surface depending on the width of the tank [8]

In the course of the study two typical ship dimensions were taken into consideration. In case of quasi static approach to the free surface effect the location of a partly filled tank does not play any role. Reversely, the dynamic approach is related to ship rolling and the location of considered tank is crucial. Therefore not only the dimensions of a model ship need to be specified but her rolling axis as well. The particulars applied in the research are given in the table 1.

Table 1. Main dimensions of considered ships

Ship particulars [m]	ship 1	ship 2
breadth B	32	20
height H	20	12,5
elevation of rolling axis KR	9,00	5,62

Regardless the ships dimensions the set of tanks is taken into account in the course of the study. They all are located in a symmetry plane of ships, although their breadth varies from 5 to 10 meters and the height from 1,5 up to 4 meters. The filling level equals 50% for each considered tanks. The tank dimensions are presented in the table 2.

Table 2. Main dimensions of considered tanks

Tank dimensions			
breadth b [m]	5	7,5	10
height h [m]	1,5	2,5	4
filling level	50%		

The considered tanks were located in four different places in both analyzed ships which is shown in Fig. 3. Each location of a tank reflects particular distance from the rolling axis of the ship and for the convenience purposes the names of locations are given according to the Fig. 3.

Fig. 3. Location of analyzed tanks within hulls of both considered ships

4. Numerical Simulations of Sloshing Phenomenon

The heeling moment due to liquid sloshing in a partly filled tank was computed with the use of CFD technique. The software FlowVision was applied. The simulations of liquid sloshing were carried out in 3D mode for the rectangular ship ballast tank.

The computational mesh applied in the course of the simulations was hexahedral type and related to two coupled reference frames, the stationary and a moving ones which is shown in Fig. 4.

Fig. 4. Computational mesh applied for CDF calculations

The Sub-Grid Geometry Resolution (SGGR) was applied where the triangulated surfaces naturally cut Cartesian cells and reconstructing the free surface [3]. The SGGR method is intended for an approximation of curvilinear boundaries on a hexahedral mesh. The method consists in natural splitting of the boundary cells by the triangulated boundaries.

The number of the obtained child cells depends on the geometry peculiarities. The child cells are arbitrary polyhedrons. The equations of a given mathematical model are approximated on the polyhedrons without simplifications. The approach enables accurate calculations in a complex domain on a reasonably coarse mesh [3]. The FlowVision code is based on the finite volume method (FVM) and uses the VOF method for free surface problems [3]. High accuracy of computation is achieved by solving the governing equations in the 'free surface' cells (the cells partly filled with liquid) [3]. The RANS (Reynolds-averaged Navier–Stokes) equation is implemented and the simulation of turbulent flows is based on the eddy viscosity concept. The semi-empirical k-ε model turbulence model was applied.

The result of the simulation comprises the general flow pattern, the velocity and pressure fields and the user-predefined heeling moment due to liquid sloshing being the most important for the conducted study.

5. Computation of Heeling Moment due to Liquid Sloshing

The heeling moment due to liquid sloshing in tanks, obtained in the course of numerical simulations, was decomposed into two components. The first one comprises the moment due to dynamic action of solid-like liquid (i.e. 'frozen') at an angle of heel equal 0 degrees. The second component of the dynamic heeling moment due to liquid sloshing covers only the moment resulting from letting free the liquid to slosh inside the tank. All moments (components) are computed about the ship rolling axis which is fixed at the symmetry plane of a vessel at an elevation given in the table 1 for both considered ships.

The component containing the moment resulting from the solid-like liquid is included in the weight distribution calculation. And the remaining dynamic component of the heeling moment due to liquid sloshing which may be called 'the free floating component' is the matter of this paper. The core idea of this approach may be expressed by the formula:

$$M_{Total_dyn} = M_{FL_dyn} + M_{Ff} \quad (1)$$

where:

- M_{Total_dyn} – total dynamic moment due to liquid sloshing in a tank;
- M_{FL_dyn} – dynamic heeling moment due to the weight of solid-like liquid in a tank;
- M_{Ff} – free floating component of the dynamic moment due to liquid sloshing.

According to the formula (1) the core component of the heeling moment due to sloshing is a difference between the total dynamic moment due to liquid sloshing and the dynamic moment due to solid-like weight in a tanks. The result is calculated in time domain, however, the most convenient way of presentation of

the free floating moment is a graph plotted versus an angle of ship's heel which is presented in Fig. 5.

Fig. 5. Free floating component M_{Ff} of the dynamic moment due to liquid sloshing plotted versus an angle of ship's heel – exemplary case

Although the heeling moment was computed in the course of time-domain calculations, the considered free floating component of the moment was plotted versus an angle of ship's heel. Then thanks to the application of the decomposition of the heeling moment (formula 1), the resultant hysteresis loop of the free floating component may be simplified by the use of a previously worked out linearization procedure [7]. The criterion of an equivalent work of moments was adopted because of the main long-term purpose of the research which is the modification of the weather criterion of ship stability assessment. This criterion is just based on the work of both the heeling moment and righting moment which justifies the proposed linearization procedure [7]. The linearization formula can be concisely shown in following notation [7]:

$$\begin{aligned} & \int_0^{\varphi_A} M_{Ff(\varphi)} \cdot d\varphi - \int_{\varphi_A}^0 M_{Ff(\varphi)} \cdot d\varphi + \int_0^{-\varphi_A} M_{Ff(\varphi)} \cdot d\varphi - \dots \\ & \dots - \int_{-\varphi_A}^0 M_{Ff(\varphi)} \cdot d\varphi = 4 \int_0^{\varphi_A} M_{Ff_LA} \cdot d\varphi = \varphi_A \cdot M_{FfA} \end{aligned} \quad (2)$$

where:

- M_{Ff} – free floating component of the dynamic moment due to liquid sloshing;
- φ – angle of ship's heel;
- φ_A – ship's rolling amplitude;
- M_{Ff_LA} – linear approximation of the free floating component of the heeling moment for a given ship's rolling amplitude;
- M_{FfA} – the value of the linear moment M_{Ff_LA} for an angle of heel equal rolling amplitude φ_A .

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 (φ_A, M_{FfA}) . Therefore the complete description of the linear approximation of the moment M_{Ff} may be done by one scalar only. Such a scalar is the value M_{FfA} of the linear free floating component due to sloshing for the angle of heel equal φ_A and obtained according to the given formula (2) [7].

The resultant characteristic of an influence of the tank's dimensions and location on the free floating component of the heeling moment due to liquid sloshing is shown in Fig. 6.

Fig. 6. Linear free floating component of heeling moment due to liquid sloshing in each of considered tanks

It ought to be emphasized that the value M_{FfA} of the heeling moment's linear free floating component depend not only on tank dimensions and location but obviously one the weight of liquid inside. Thus the wider and higher tanks are considered the greater value of moment M_{FfA} is noticed which can be seen in Fig. 6 in the form of evident nonlinearities. This effect in the results presentation can be avoided thanks to application a simple operation. Instead of presentation the value M_{FfA} of linear free floating component the ratio M_{FfA}/q could be plotted, where q is just the weight of liquid in each tank calculated as mass times gravity acceleration. The quotients moment over liquid weight which can be truly called moment's arms, plotted versus tank's breadth and height reflect the results presented in Fig. 6 omitting the blurry effect of variable liquid weight. Such approach is presented in Fig. 7.

*Fig. 7. Linear free floating arm versus breadth and height of the considered tank
(each surface reflects one location of the tank)*

The graph presented in Fig. 7 gathers the computation results for all four considered tank's locations. It can be seen that the higher tank's elevation the steeper characteristic obtained. However, the almost linear trends for every single tank location could be best seen when the plots are shown separately like in Fig. 8.

*Fig. 8. Linear free floating arm versus breadth and height of the considered tank
(separate graphs for each location of the tank)*

6. Conclusion

The study presented in the paper is focused on the dynamic effects of liquid sloshing in partly filled ship tanks. As the free surface effect is taken into account in the course of a routine stability calculations, the authors find a question about dynamic approach as justified.

The novel approach for the decomposition of the dynamic heeling moment was applied and together with the linearization procedure it enabled the convenient way of heeling moment presentation and analysis.

The results of the study enables an assessment of the influence of tank dimensions and location (in terms of elevation above the base line) on the free floating component of heeling moment due to liquid sloshing in tanks. The obtained characteristics of quotient M_{FFA}/q being the arm of heeling moment's linear free floating component are very close to linear ones. The analyzed arm linearly increases with the rise in breadth of the tank and this arm increases with the drop of tank's height. Such a characteristics clearly reveals the wide and relatively low tanks result in high wave type disturbances during liquid sloshing.

The study described in the paper may be a contribution to the ship safety estimation methods. The results suggest the need for further research work on the liquid sloshing phenomenon onboard seagoing ships. The future steps of the research shall systematically focus on further parameters influencing the heeling moment due to liquid sloshing in ships' tanks.

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