

A Method of Assessment of the Liquid Sloshing Impact on Ship Transverse Stability

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ABSTRACT: Liquid sloshing phenomenon taking place in partly filled ships' tanks directly affects the stability of a vessel. However, only static calculations are carried out onboard ships nowadays and static transfer of liquid weight is taken into account in the course of routine stability calculation. The paper is focused on a dynamic heeling moment due to liquid sloshing in tanks onboard ships. The set of numerical simulations of liquid sloshing taking place in moving tanks is carried out. The realistic range of geometric parameters is taken into account. The conducted CFD simulations are experimentally verified. Finally, the method of an assessment of the liquid sloshing impact on ship transverse stability is worked out. The key point of the method is a dynamic coefficient describing relation of the researched dynamic heeling moment and the quasi-static one in terms of dynamic stability of a vessel which is related to the weather criterion of ship stability assessment.

1 INTRODUCTION

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 their stability.

Ship stability is a term used to describe the tendency of a ship to return back to her equilibrium when she is inclined from an upright position [5]. 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. The complementary definitions lead to point out that the stability of a ship is an element of her operational safety qualifying factors.

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 [5]. 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 [4].

The ship stability criteria qualify the shape of the righting arm curve. In addition, the weather criterion is to ensure the sufficient stability of a ship to withstand the severe wind gusts during rolling [4]. Although the weather criterion reflects 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 remaining criteria are based on the statistics of historical disasters only [3]. The modern and still developing approach towards ship stability

qualification is an implementation of performance-based stability criteria in the future. They are based mainly on the risk assessment [5] however, it is still far from common use onboard ships.

Regardless the approach towards ship stability evaluation, the physical background of phenomena taking place onboard ought to be taken into account. In case of contemporary prescriptive stability standards, the righting and heeling arms need to be obtained and compared. Then the work of the righting arm enabling accumulation and then dissipation of the energy could be compared to the energy provided to the ship by external forces which is called the energy balance method for dynamic stability calculation [5]. The balance of righting arm (righting moment) and heeling arm (heeling moment) shall comprise all significant components of each moment and among others the heeling moment due to liquid sloshing in a partly filled moving tank too.

In the light of ship stability related concepts, the accuracy of ship's transverse stability assessment is an important problem in vessels operation process. Both approaches towards ship stability assessment known nowadays call for characteristics of heeling moment due to liquid sloshing in tanks. This need justifies the research program focused on the liquid sloshing phenomenon.

2 FREE SURFACE EFFECT AND LIQUID SLOSHING PHENOMENON

The intact ship stability assessment is carried out onboard generally on the basis of the IMO IS-Code. Thus, the standard stability measures like a metacentric height, righting arm curve etc. are in common use. According to the IMO recommendations the righting arm curve shall be corrected for the effect of free surfaces of liquids in tanks. The correction may be done by any of two accepted methods [4]:

- 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).

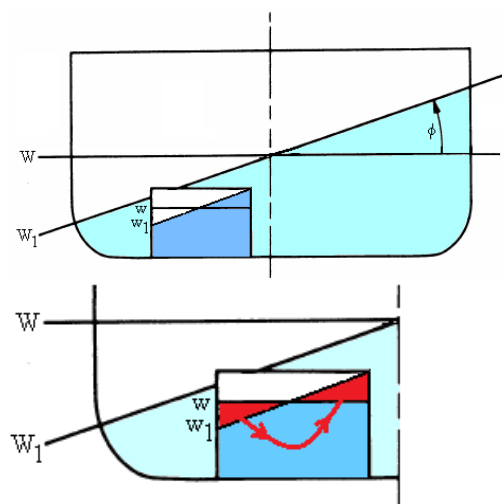


Figure 1. Flat surface of waterline and liquid's free surface in partly filled tank (left) and the quasi-static transfer of fluid mass due to ship heeling (right)

Both 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 tanks within the hull of a ship and the location 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).

The liquid sloshing phenomenon takes place in partly filled ships tanks. As a tank moves, it supplies energy to induce and sustain the fluid motion. Both the liquid motion and its effects are called sloshing. The effect of water motion inside the tank is the pressure field on the tank's structure. The interaction between ship's and tank's structure and the water sloshing inside the tank consists in the permanent transmission of the energy [1]. As the ship rolls, the walls of the partly filled tank induce the movement of water. Then the water press against the opposite situated tank's walls and return the energy to the ship, then taking the next portion enabling the counter-direction movement. The exemplary general view on the liquid sloshing phenomenon taking place inside a model tank swinging during an experimental research is shown in Fig. 2.



Figure 2. Exemplary shape of a free surface of liquid inside a partly filled model tank (own research) – it may be clearly seen that the free surface is far different than assumed within the quasi-static approach (ref. to Fig. 1)

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 [11]. 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 the hull of a ship, rolling period and others. Due to the noticed nonlinearity a description of the sloshing phenomenon is relatively complex, however, the energy characteristics seem to play an important role, especially when referred to the ship dynamic stability requirements.

3 CFD MODELING OF LIQUID SLOSHING PHENOMENON

The noticeable weaknesses of the static approach towards the free surface correction and its application in the course of ship stability assessment are commonly known, therefore, a number of studies is still undertaking worldwide. Generally the main stream of researches comprises two corresponding trends i.e. numerical simulations of liquid sloshing phenomenon and experimental tests. Both approaches are coupled and they complement each other.

At the present state-of-the-art numerical simulations require an experimental validation allowing adjusting of a set of input parameters like a computational mesh, a time step, etc. The features being usually validated are dynamic pressure at some selected points and a shape of the free surface of liquid.

The research project carried out in the Department of Ship Operation at the Gdynia Maritime University was focused on the ship stability issues with regard to liquid sloshing phenomenon in partly filled tanks. The application for this task a CFD technique of numerical simulations of liquid sloshing flow is relatively cost-effective technique allowing many runs of simulations covering the wide scope of conditions. Contrary to this, the experimental tests are rather costly and time-consuming, therefore every single run of experiment needs to be carefully planned and justified.

The applied numerical solving a flow problem inside moving tanks includes several steps [2]:

- creating a computational domain;
- specifying a mathematical model;
- specifying initial and boundary conditions;
- specifying a computational mesh;
- calculations;
- visualization and analysis of results.

All the listed steps were carried out for the most typical rectangular ships tanks. The size and location of the tank correspond with its common location [9]. The range of angular motion was set for 40 degrees and it reflects the very heavy sea conditions in extremely stormy weather [8] (Fig. 3).

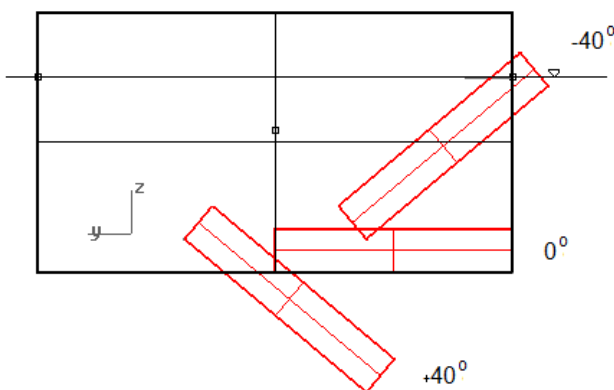


Figure 3. Ship rolling amplitude (range of angular motion of the tank) applied in the course of CFD modeling of liquid sloshing in considered tanks

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. The arrangement of the reference systems is presented in Fig. 4.

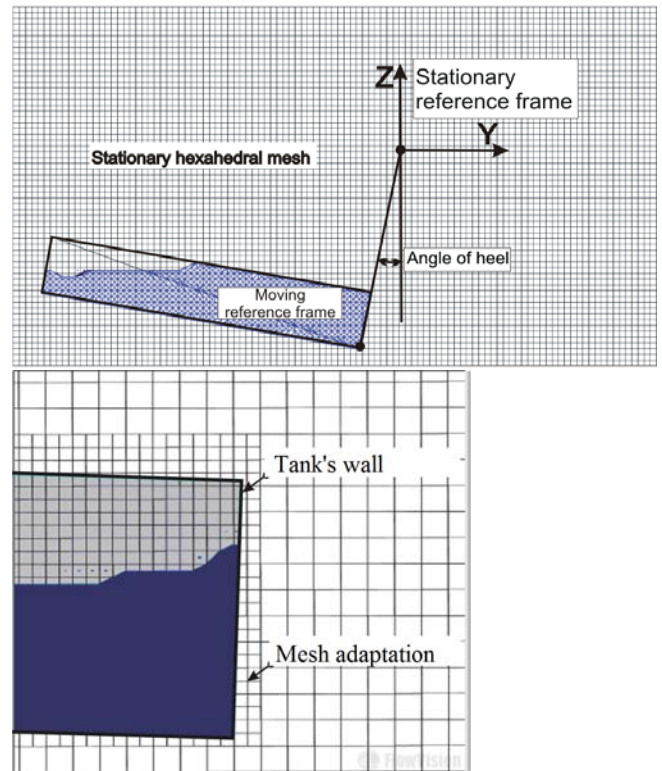


Figure 4. Computational mesh and two coupled reference frames systems

The three-dimensional simulations of the sloshing phenomenon were carried out by the use of FlowVision code being an universal and flexible tool designed for modeling of liquids dynamics. The code is based on the finite volume method (FVM), and uses the VOF method for free surface problems [2]. The RANS (Reynolds-averaged Navier-Stokes) equation is implemented which is the time-averaged equations of motion for fluid flow. Simulation of turbulent flows is based on the eddy viscosity concept. The turbulent eddy viscosity contributes the diffusion coefficients in the Navier-Stokes and convection-diffusion equations [2]. The semi-empirical $k-\epsilon$ model turbulence model was applied.

The result of the simulation comprises mainly the general flow pattern and the velocity and pressure fields. The exemplary shape of a free surface is shown in Fig. 5.

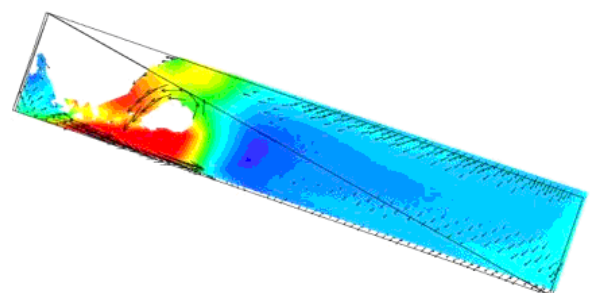


Figure 5. Computed shape of a free surface in a moving tank (example)

Moreover, the user defined parameter, i.e. the heeling moment due to liquid sloshing inside partly filled tank which is essential from the conducted research point of view, was also calculated. The heeling moment M vector was calculated according to the following formula:

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

where:

S – the wetted surface of the tank's shall;

\mathbf{r} – the position vector of the considered point on the tank's wall;

\mathbf{n} – the normal vector;

p – the local pressure on the tank's wall.

Due to the prevailing 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 may be described by one spatial component only, as follows [6]:

$$\mathbf{M} = [M_x, M_y, M_z] = [M_x, 0, 0] \quad (2)$$

where:

M_x, M_y, M_z – spatial components of \mathbf{M} vector, determined about the x, y and z axis in the reference system related to the vessel.

For further use the sole non-zero component M_x of the computed heeling moment due to liquid sloshing which is described by the formula (2) was named the total dynamic moment and marked $M_{Total, dyn}$. Such heeling moment was the subject for post processing and reasoning.

4 EXPERIMENTAL RESEARCH IN MODEL SCALE

Although the numerical simulation of liquid sloshing in a partly filled tank is a powerful technique, it still requires an experimental verification for some cases. Generally, the experiment is commonly found as an unambiguous prove for the correctness of numerical computations. Therefore, the experimental research into the sloshing phenomenon was carried out in Ship Operation Department at the Gdynia Maritime University. It enabled to measure the dynamic pressure distribution on the side wall of the model tank and in its upper corner and furthermore, to record a shape of free surface for any angle of tank's tilt. The experimental investigation required the arousing of the sloshing phenomenon. After that the dynamic pressure time history in selected spots was measured and recorded. To achieve this the test apparatus was designed and built.

The main part of the apparatus is a tank equipped with pressure transducers. The tank is forced to oscillating motion by the hydraulic drive mechanism, thus exciting the water sloshing inside the tank. The dimensions of the model tank are: breath – 1,040 m, length – 0,380 m, depth – 0,505 m. The general view of

the testing apparatus and the location of dynamic pressure sensors is shown in Figure 6.

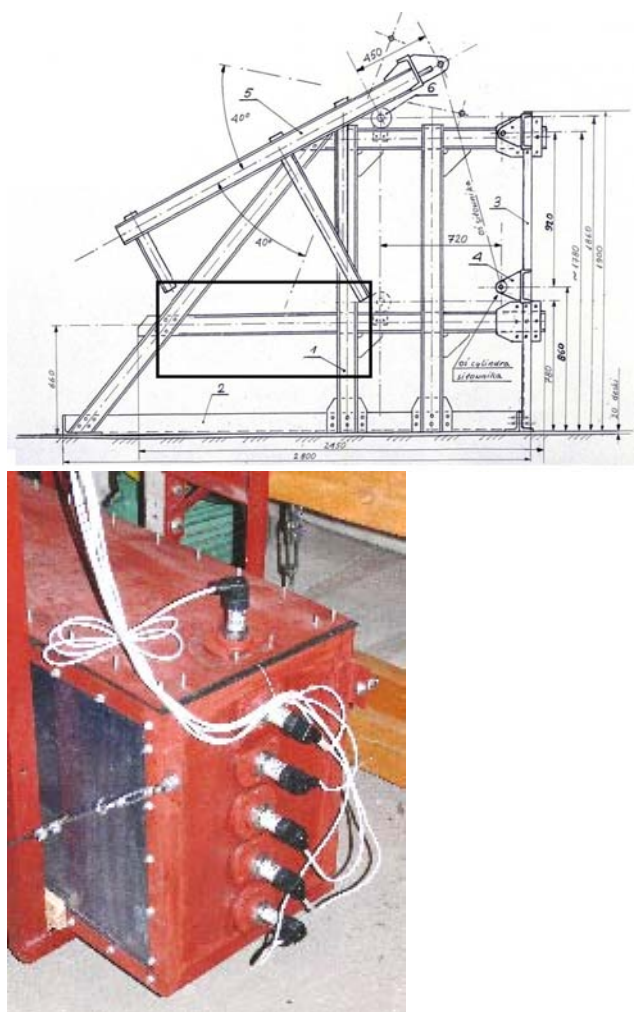


Figure 6. Experimental setup: general layout (left) and pressure gauge arrangement (right)

The pressure signal, measured by the transducers, consists of two components. One of them is called non-impulsive dynamic pressure and the other one impulsive pressure, or impact pressure [1]. The non-impulsive dynamic pressure is slowly varying. It is the result of the global movement of liquid in the tank and it affects the transverse stability of a ship.

Despite the dynamic pressure distribution the shape of free surface of liquid sloshing in the tank was recorded. The liquid distribution and a velocity field are governed mostly by the inertia of liquid mass and a pressure field. As a consequence, the correct modeling of liquid's free surface emerges as a strong prove for the correctness of the CFD-based numerical simulations of sloshing flows. The exemplary comparison of free surfaces recorded in a model tank during experiment and computed in the course of simulations is shown in Fig. 7.

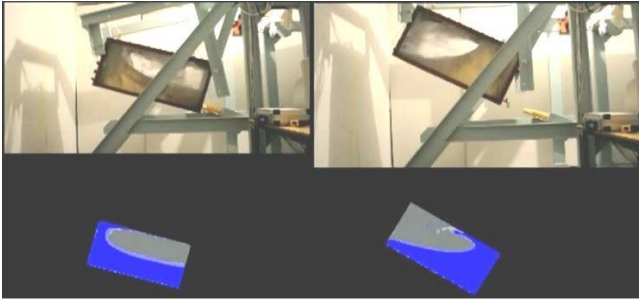


Figure 7. Comparison of a shape of free surface: experiment (upper photos) and numerical simulations (lower graphics)

The pressure history in the control points of the tank obtained in the course of the experiment were compared to the computed ones. Both experimental results the pressure and the free surface meet relevant results achieved by the use of CFD simulations. Consequently, the results of simulations were acknowledged as correct and reliable.

5 CHARACTERISTICS OF DYNAMIC HEELING LEVER DUE TO LIQUID SLOSHING IN TANKS

The result of the numerical simulations of liquid sloshing which is most essential from the conducted research point of view, is the total dynamic heeling moment due to the analyzed phenomenon. It is obtained in time domain, however, since the momentary angle of ship's heel is known for every time step of CFD computations, the heeling moment may be plotted versus an angle of heel as well. This is a convenient approach for results visualization.

Regardless the way of display of the heeling moment, the momentary values of heeling moment depends not only on the geometry of the tank (like in case of quasi-static approach) but also on the location of the considered tank. This circumstance significantly impedes inferring about the influence of any parameter. The suggestion and inspiration regarding addressing the described problem can be found in the static free surface correction and the contemporary way of ship stability calculation.

The total static heeling moment due to a presence of liquid inside a tank is divided into two components. One of them reflects the moment of liquid's weight without any changes of shape during ship heeling. One may find such liquid as a "frozen" one or generally as a solid [7]. This component is included in standard weights and moments calculation sheet and it is not revealed as a free surface effect [4]. The second component of the static heeling moment due to tank's partly filling comprises the fluid transfer calculated for each angle of heel. This component reveals the free surface correction.

The similar reasoning may be applied to the dynamic heeling moment due to liquid sloshing. The total value of the moment could be decomposed into two components. The first one comprises the moment due to dynamic action of liquid "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. Analogously to the

static case, the component containing the moment coming from the frozen-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 further consideration. The core idea of an analogy in this approach may be expressed by the formulas:

$$M_{Total_stat} = M_{FL_stat} + M_T \quad (3)$$

$$M_{Total_dyn} = M_{FL_dyn} + M_{Ff} \quad (4)$$

where:

M_{Total_stat} – total static moment due to a presence of liquid with free surface in a tank;

M_{FL_stat} – static heeling moment due to the weight of frozen-like liquid in a tank;

M_T – static heeling moment of fluid transfer calculated for each angle of heel;

M_{Total_dyn} – total dynamic moment due to liquid sloshing in a tank;

M_{FL_dyn} – dynamic heeling moment due to the weight of frozen-like liquid in a tank;

M_{Ff} – free floating component of the dynamic moment due to liquid sloshing.

On the basis of the formula (4) the free floating component of the heeling moment can be extracted. The result of applied decomposition is shown in Fig. 8.

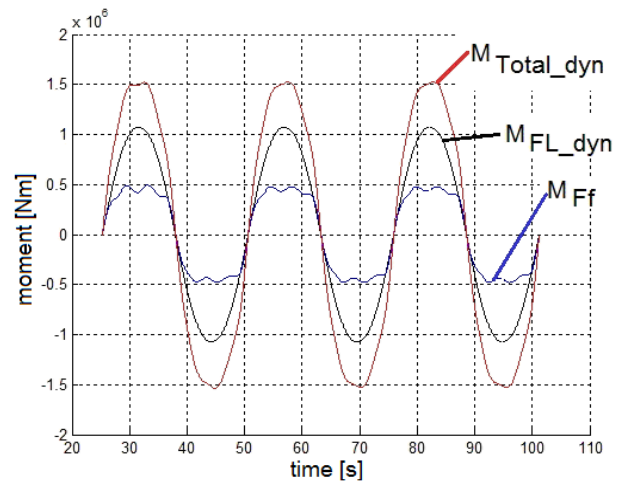


Figure 8. Decomposition of the heeling moment due to liquid sloshing carried out according to the formula (4) –sample case

According to the formulas (3) and (4) it may be stated that the frozen-like mass of liquid in both equations refers to exactly the same volume of liquid while the only difference is the pace of ship heeling (quasi-static vs. dynamic approach). Thus, the remaining component of the total heeling moment in both approaches may be compared. Such a comparison carried out for two exemplary cases is shown in Fig. 9.

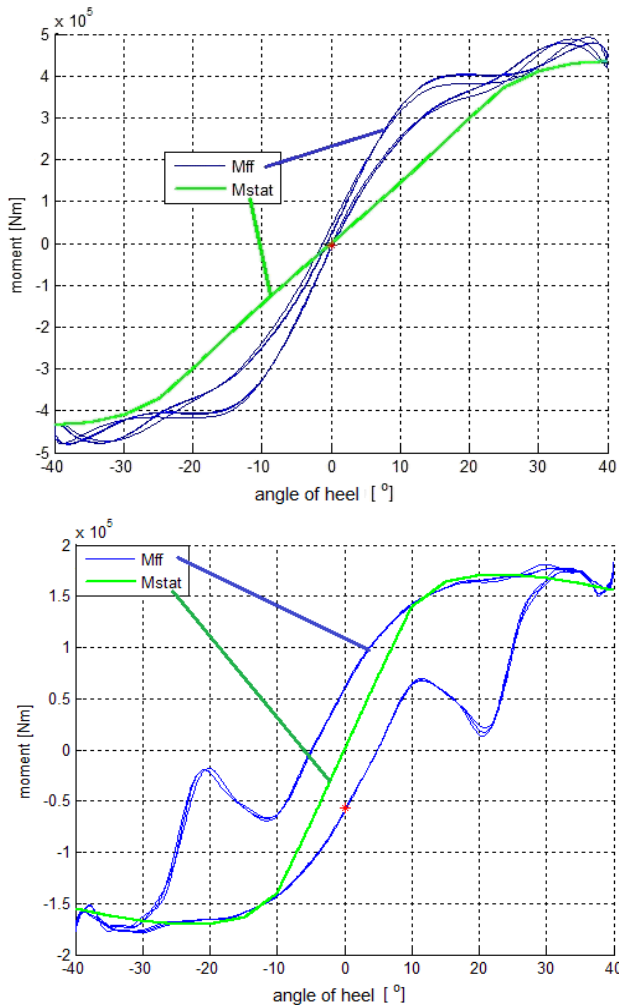


Figure 9. Comparison of M_{ff} and M_{stat} components of the heeling moment due to liquid motion in partly filled tanks – sample cases

The most significant remarks related to the comparison of M_{ff} and M_{stat} components of the heeling moment due to liquid motion in partly filled tanks, refer to two main issues. Firstly, it is possible emergence of both: quasi-static approach (e.g. free surface effect) produces the results more severe to a ship stability than dynamic approach or reversely the dynamic calculation is more demanding in terms of ship stability than static one. Secondly, there is a lack of an objective measure enabling clear classification which of the analyzed moments produces more or less severe results from the ship stability point of view.

Addressing the problem of comparison of the M_{ff} and M_{stat} components of the heeling moment due to liquid motion, the aggregative variable was worked out and named the “dynamic coefficient”. This coefficient refers to the dynamic stability of a vessel or in other words to the weather criterion of the intact ship stability assessment which is based on the energy balance method of stability calculation [5].

In the typical case of asymmetric location of ship tanks, the dynamic coefficient needs to be calculated separately for a port side tank (coefficient kd_L) and a starboard one (kd_P respectively). The definitions of applied coefficients are given by following formulas:

$$kd_P = \frac{W_{M_{Ff-P}}}{W_{M_{T-P}}} = \frac{\int_0^{\varphi_A} M_{Ff} \cdot d\varphi - \int_0^{\varphi_A} M_{Ff} \cdot d\varphi}{\int_0^{\varphi_A} M_T \cdot d\varphi - \int_0^{\varphi_A} M_T \cdot d\varphi} \quad (5)$$

$$kd_L = \frac{W_{M_{Ff-L}}}{W_{M_{T-L}}} = \frac{\int_0^{-\varphi_A} M_{Ff} \cdot d\varphi - \int_0^{-\varphi_A} M_{Ff} \cdot d\varphi}{\int_0^{-\varphi_A} M_T \cdot d\varphi - \int_0^{-\varphi_A} M_T \cdot d\varphi} \quad (6)$$

where:

- $W_{M_{Ff-P}}$ - work of moment M_{Ff} during ship’s heeling to starboard side;
 - $W_{M_{T-P}}$ - work of moment M_T during ship’s heeling to starboard side;
 - $W_{M_{Ff-L}}$ - work of moment M_{Ff} during ship’s heeling to port side;
 - $W_{M_{T-L}}$ - work of moment M_T during ship’s heeling to port side;
 - φ - angle of ship’s heel;
 - φ_A - amplitude of rolling;
- remaining symbols like in formulas (3) and (4).

On the basis of introduced dynamic coefficients (formulas 5 and 6) a set of sample calculations was carried out. The ship particulars taken into account reflect round Panamax size and they were following: breadth $B=32$ m, height $H=20$ m, elevation of rolling axis $KR=9$ m. The location of analyzed sample tanks is shown in Fig. 10.

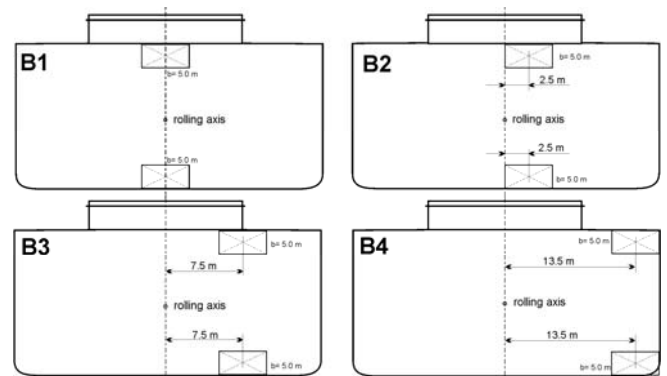


Figure 10. Arrangement of considered tanks in ship’s hull

Only one side of the ship (e.g. starboard side) was taken into consideration to perform the set of sample calculations one breadth of the tank $b_z=5$ m and two possible heights of tanks $h_z=1,5$ m and $h_z=2,5$ m. The dynamic coefficient kd_P was computed which is presented in Fig. 11.

The computation of the dynamic coefficient kd_P was carried out only for a sample set of possible cases, thus the quantitative analysis cannot be representative for any potential sizes and locations of ship tanks. However, the interpretation of the results is analogous for any cases at any ship.

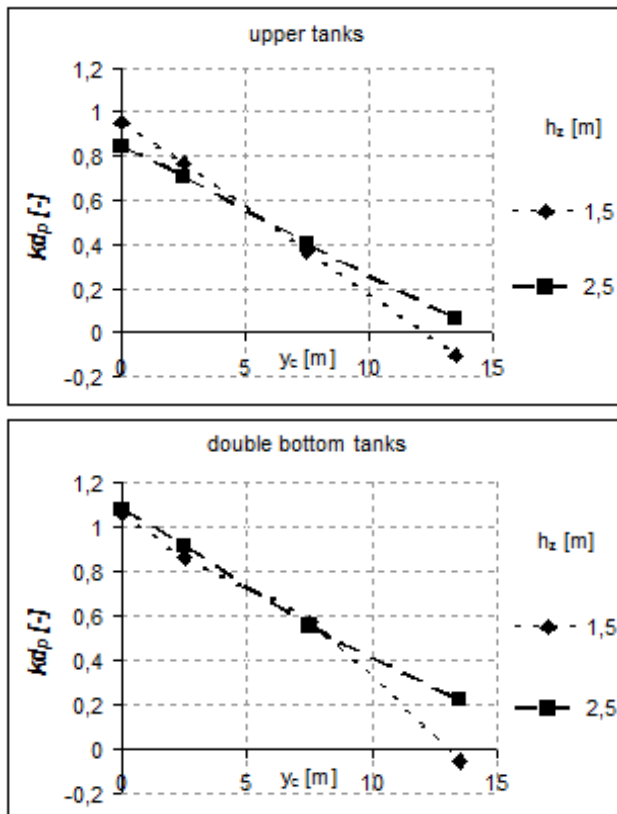


Figure 11. Correction factor k_{dp} for different location and height of considered tanks

It ought to be emphasized that the considered dynamic coefficient comprises only the effects of the M_{ff} and M_{stat} components of the heeling moment due to liquid motion. The value $k_{dp} = 1$ indicates the dynamic effect of liquid sloshing equal to the static one in terms of ship transverse stability. The value $k_{dp} = 0$ denotes a lack of the dynamic effect of liquid sloshing in a partly filled tank which is possible due to the wave character of sloshing flow and a noticed phase shift. Such a phenomenon is utilized in anti rolling devices (flume tanks) and it is also encountered during liquefied cargo carriage [10].

6 CONCLUSION

The study presented in the paper is focused on the dynamic effects of liquid sloshing taking place in partly filled ship tanks. The decomposition of the dynamic heeling moment due to liquid sloshing was applied. Then the further processing of a free floating component enabled implementation of a novel variable named a dynamic coefficient. The coefficient corresponds with the energy balance method of ship dynamic stability calculations and thanks to this it is compatible with the weather criterion recommended by the IMO Intact Stability Code.

A set of sample calculation of the dynamic coefficient was carried out. The results reveal the possibility of greater impact of sloshing liquid in a tank then it is expected on the basis of contemporary quasi-static calculations. However, in most analyzed cases the impact of liquid sloshing was found smaller then it is supposed on the basis of quasi-static approach.

Such a conclusion may be important from the economical point of view. Ship stability standards quite often restrict the capability of a vessel to carry as much cargo as may be physically loaded. The so called safety margin is maintained. The common application of the proposed dynamic coefficient could make the stability requirements less severe then nowadays. It may be especially important in the age of economical crisis and a worldwide tendency to cost optimization. Any extra cargo carried over the current restrictions contributes to the ship operator's revenue. It could be accepted when without any significant decay of safety standard onboard. Thus, arousing of a discussion on IMO forum seems to be justified.

ACKNOWLEDGMENT

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