AN INVESTIGATION INTO THE INFLUENCE OF TANK FILLING LEVEL ON LIQUID SLOSHING EFFECTS ONBOARD SHIPS - STATIC AND DYNAMIC APPROACH

Przemysław Krata, Wojciech Wawrzyński, Jacek Jachowski, Wojciech Więckiewicz

Gdynia Maritime University
Department of Ship Operation
Jana Pawła II Av. 3, 81-345 Gdynia, Poland
tel.: +48 58 6901160, +48 58 6901154
+48 58 6901149, fax: +48 58 6901101
e-mail: p.krata@wn.am.gdynia.pl
keswwaw@am.gdynia.pl, jjaca@o2.pl, wiecwoj@op.pl

Abstract

The commonly discussed main features of maritime transport are usually its safety and effectiveness. One of the most critical features of seagoing ships related to her safety is stability influencing ship's overall sea keeping performance. Vessels' stability calculation and evaluation, made on-board nowadays, is based on the stability criteria published by the ship's classification societies. According to the IMO recommendations, the righting lever curve should be corrected for the effect of free surfaces of liquids in tanks. IMO-recommended methods of free surface correction calculation consider the static attitude towards the liquid sloshing phenomenon only. They also do not consider the location of the tank within the hull of the ship and the location of a rolling axis. The more precise and more realistic approach towards liquid movement is complex analysis of liquid sloshing phenomenon. As liquid sloshing taking part in partly filled ship's tanks is an important element affecting safety of maritime transportation process, there is a need for detailed analyses related to crucial parameters of the considered phenomenon. The paper is focused on an influence of tank's filling level on effects of aroused and sustained movement of ballast water, fuel and other liquids carried onboard ships. Both static and dynamic approaches towards the problem are utilized. The analytical methods for liquid weight transfer calculation and numerical simulations of the liquid sloshing phenomenon are applied. The simulations of liquid sloshing are based on Reynolds-averaged Navier-Stockes equation and they take into account the viscosity of liquid. The resultant heeling moment is decomposed into components enabling extraction of dynamical component differentiating the applied method from old static ones. The results of the study contribute to more precise ship safety evaluation.

Keywords: liquid sloshing, free surface effect, dynamic heeling moment, partly filled ship's tank

1. Introduction

In the age of globalization, the importance of overseas transportation of goods is vital. The commonly discussed main features of maritime transport are usually its safety and effectiveness. However, the effectiveness of a transportation process is a complex and important matter, 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 sea keeping performance.

Ship stability remaining crucial factor determining sea keeping of ships is a component of many researches leading to the increase in understanding of the safety qualifying factors. Stability against capsizing and excessive heeling is one of the most fundamental requirements considered by naval architects when designing cargo vessels and by their operators in the course of sailing and cargo handling [1]. The stability of a vessel belongs to operational characteristics enabling cost effective and safe operation [1]. 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.

One of the problems related to ship stability and its overall performance is an influence of moving liquids in partly filled tanks. Generally moving masses need to be avoided, however it is impossible to evade them at all. The cargo securing procedures ensure an extinction of loose cargo onboard but some free surfaces of liquids in ships' tanks are inevitable. The crucial groups of tanks onboard ships, which may be partly filled, are ballast tanks. They can be classified according to their purpose as follows:

– trimming tanks (fore and after peaks) which are utilized very often as partly filled due to the need for precise trimming of a ship, so the ballast water level is adjusted according to the variable requirements, thus providing free surface of liquid,

– stability tanks improving ship's stability performance due to a decrease in the vertical centre of gravity (usually double bottom tanks located between an engine room and a fore peak creates this group); quite often the breadth of these tanks equals half breadth of a ship or even sometimes it equals full ship's breadth (in ship's fore region) therefore the free surface of liquid can be massive in these tanks so generally they should be full or empty during voyage,

– list control tanks (side tanks) which are usually located amidships and due to their function quite often partly filled with free surface,

– strength control tanks utilized to adjust longitudinal weight distribution (fore and after peaks, double bottom tanks, side tanks and sometimes even cargo holds prepared for ballasting) which are very often partly filled to reduce excessive sheering force and bending moment and routinely they provide free surface of liquid,

– special purpose tanks like for instance anti-rolling tanks (flume) or anti-heeling tanks, which are usually filled up to the 50% level, providing free surface.

Regardless the exact purpose of ballast tanks onboard, their total volume and resulting from it total weight of ballast water is significant which is shown in Fig. 1. This justifies focusing on this group of tanks in the course of the conducted research.
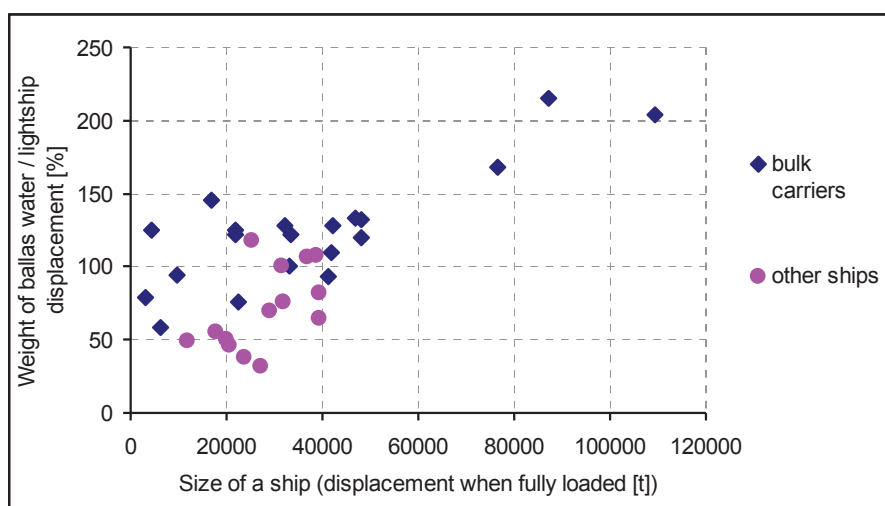

Fig. 1. Relation of ballast water weight to the lightship weight

The graph (Fig. 1) reveals that the total weight of ballast water carried onboard may reach and even exceed the lightship weight among ships other than bulk carriers. Moreover, ballast water weight can be twice a lightship in case of bulk carriers. Obviously not all the tanks are partly filled at the same time but some of them can be which creates the need for stability calculations comprising the phenomenon of moving liquids in tanks.

2. Contemporary static approach towards free surface corrections onboard ships

Vessels' stability calculation and evaluation, made onboard 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 – including last edition dated 2009 - are known as the Intact Stability Code [3].

According to the IMO recommendations, the righting lever curve should be corrected for the effect of free surfaces of liquids in tanks. The free surface correction needs to be applied in case of partly filling of any tank while a tank is considered as partly filled up to the level equal 98% of its volume. The correction may be done by any of the accepted methods [3]:

– 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.

The last method is very common since the correction is based on the same formula, which is applied in the course of initial stability calculation (for a metacentric height correction):

$$\Delta GM = \frac{i_B \cdot \rho}{D},$$ (1)

where:

i_B – moment of inertia of tank's horizontal projection at the 0 degrees angle of heel,

ρ – density of a liquid in partly filled tank,

D – displacement of a ship.

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. 2).
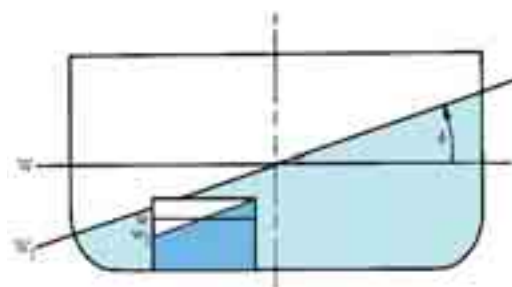

Fig. 2. Flat surface of waterline and liquid's free surface in partly filled tank

Generally the formula (1) based on *ΔGM* correction ought to be applied only for relatively small angels of ship's heel. Nevertheless, for the sake of simplicity, it is in common use worldwide. The literature review reveals that the correction *ΔGM* is found as safer then the correction based on the moment of fluid transfer (for each angle of heel) due to some extra stability margin provided. However, both static methods create exactly the same results when a set of conditions is satisfied:

– a tank is wall-sided,

– there is a lack of contact of liquid surface with tank's bottom or roof (see Fig. 3),

– an angle of ship's heel is small enough to accept tgφ ≈ sinφ.

Fig. 3. Possible contact of liquid surface with tank's bottom (A) or its top (B)

The specified conditions ensuring equal value of a free surface correction calculated with the use of any of recommended methods can be satisfied only for limited range of angles of heel. Moreover, the range depends on tanks height to breadth ratio. Despite the limitations, the method based on the formula (1) is common worldwide. The research carried out among a large number of cargo vessels revealed a great importance of proper free surface effect determination due to the significant values of frequently noticed *ΔGM* corrections, which is presented in Fig. 4.
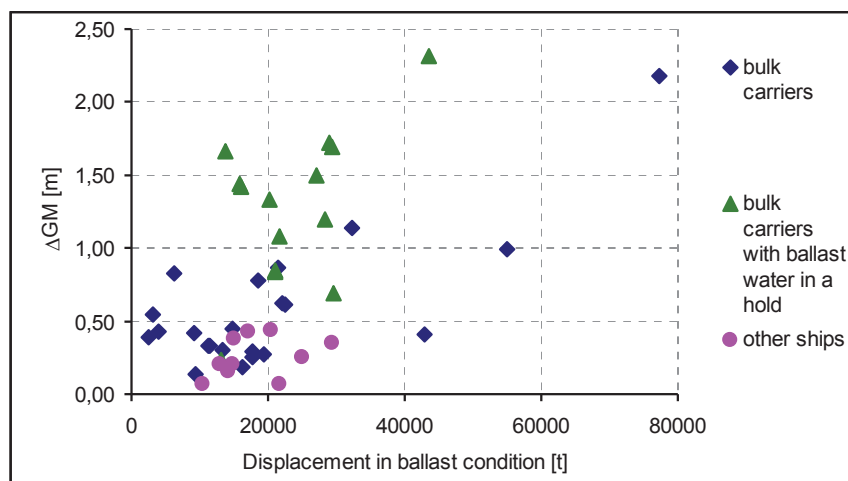

Fig. 4. Free surface correction of cargo ships in ballast condition for a wide range of ship size and type

3. CFD-based technique of computation of heeling moment due to liquid sloshing

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 support each other.

At the present state-of-the-art numerical simulations require an experimental validation allowing adjusting of a computational mesh, a time step and a set of input parameters. 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 is focused on the ship stability issues with regard to liquid sloshing phenomenon in partly filled tanks. The application for this task a 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 extremely 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 tank. The size and location of the tank correspond with its common location in a double bottom of a ship and the range of angular motion reflects the very heavy sea conditions in extremely stormy weather that is presented in the Fig. 5.
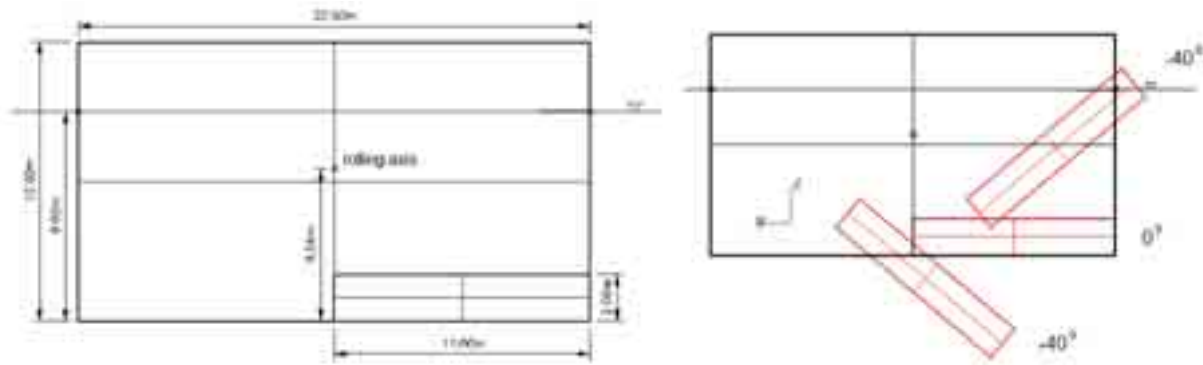
Fig. 5. Location, dimensions and a range of angular motion of the tank

The computational mesh applied in the course of the simulations was hexahedral type and related to two coupled reference frames, the stationary and moving ones. The arrangement of the reference systems is presented in Fig. 6.
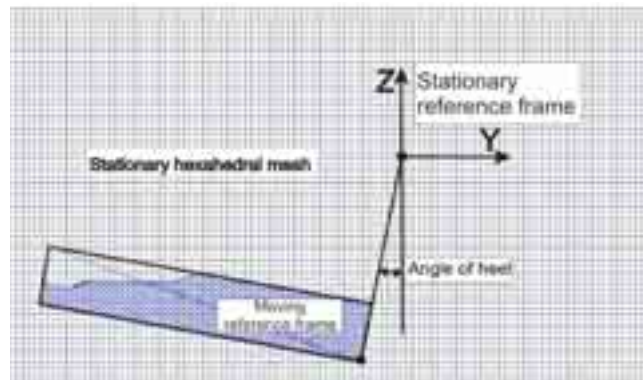

Fig. 6. Computational mesh and two coupled reference frames systems

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 modelling 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 equation of motion for fluid flow. Simulation of turbulent flows is based on the eddy viscosity concept. The turbulent eddy viscosity enters the diffusion coefficients in the Navier-Stokes and convection-diffusion equations [2]. The semi-empirical k-ε model turbulence model was applied.

The result of the simulation comprises the general flow pattern and the velocity and pressure fields. The exemplary shape of a free surface is shown in Fig. 7.
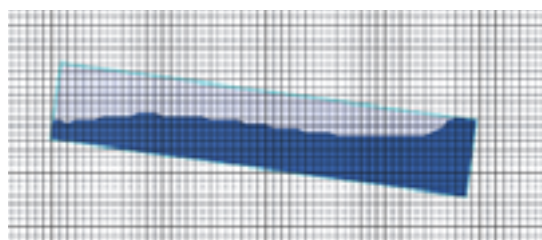

Fig. 7. Computed shape of a free surface in a moving tank (example)

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:

$$\mathbf{M} = \int_S \mathbf{r} \times \mathbf{n} \cdot p \, ds \,, \tag{2}$$

where:

S – the wetted surface of the tank's shall,
r – the position vector of the considered point on the tank's wall,
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 [4]:

$$\boldsymbol{M} = \left[M_x, M_y, M_z\right] = \left[M_x, \quad 0, \quad 0\right], \tag{3}$$

where:

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

4. Influence of tank filling level on heeling moment due to liquid sloshing – applied method and results of computation

The conducted research was based mainly on the results of numerical simulations of sloshing phenomenon carried out with the use of *FlowVision* package as described in chapter 3. The geometry of a tank was constant as well as the angular motion amplitude and the ship rolling period. The parametric approach comprises wide variety of tank's filling level reaching from 5% up to 95% of tank's volume. The exemplary graph presenting the computed heeling moment versus an angle of ship's heel is shown in the Fig. 8.
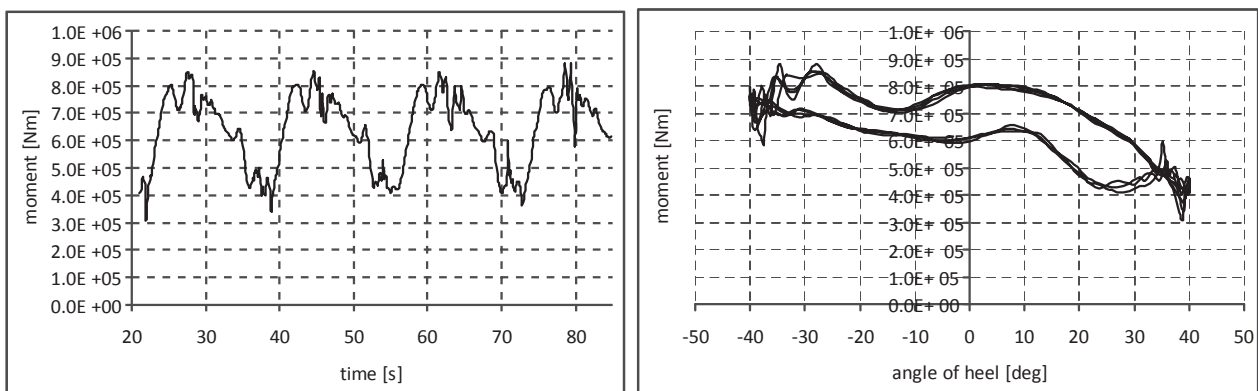

Fig. 8. Heeling moment due to liquid sloshing in the model tank – results of CFD computation (exemplary case)

The graph presented in the Fig. 8 contains a hysteresis loop and furthermore, the momentary values of heeling moment depend not only on the dynamics of liquid sloshing inside the tank but also on the location of the considered tank. This circumstance significantly impedes inferring about the influence of any parameter, e.g. the considered tank's filling level on the heeling moment due to liquid sloshing. Moreover, the linearization based on the equivalent work method cannot be easy applied for the side tanks since the values of computed heeling moment are positive only [4].

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 [4]. This component is included in standard weights and moments calculation sheet and it is not revealed as a free surface effect. 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 this paper. The core idea of an analogy in this approach may be expressed by the formulas:

$$M_{Total\_stat} = M_{FL\_stat} + M_T \,, \tag{4}$$

$$M_{Total\_dyn} = M_{FL\_dyn} + M_{Ff} \,, \tag{5}$$

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.

The free floating component of the heeling moment due to liquid sloshing can be obtained according to the formula (5) as shown in Fig. 9.
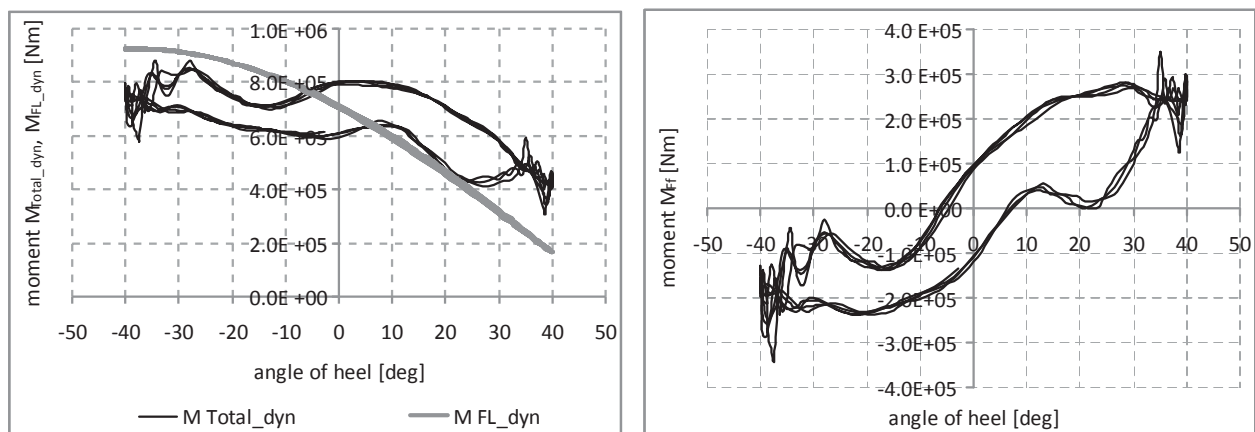

Fig. 9.   Free floating component of the heeling moment due to liquid sloshing in the model tank and the consecutive steps of its determination according to the formula (5) (exemplary case)

After an application of the proposed decomposition of the heeling moment due to liquid sloshing, the resultant hysteresis loop of the free floating component may be simplified by the use of a linearization procedure. The criterion of an equivalent work of a moment 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 [4]. The linearization formula can be concisely shown in following notation:

$$\int_{0}^{\varphi_A} M_{Ff(\varphi)} \cdot d\varphi + \int_{\varphi_A}^{0} M_{Ff(\varphi)} \cdot d\varphi = 2\int_{0}^{\varphi_A} M_{Ff\_LA} \cdot d\varphi,$$ (6)

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.

The results of computation of the linear approximation of the free floating component of the heeling moment due to liquid sloshing in partly filled ship's tank is presented in Fig. 10.
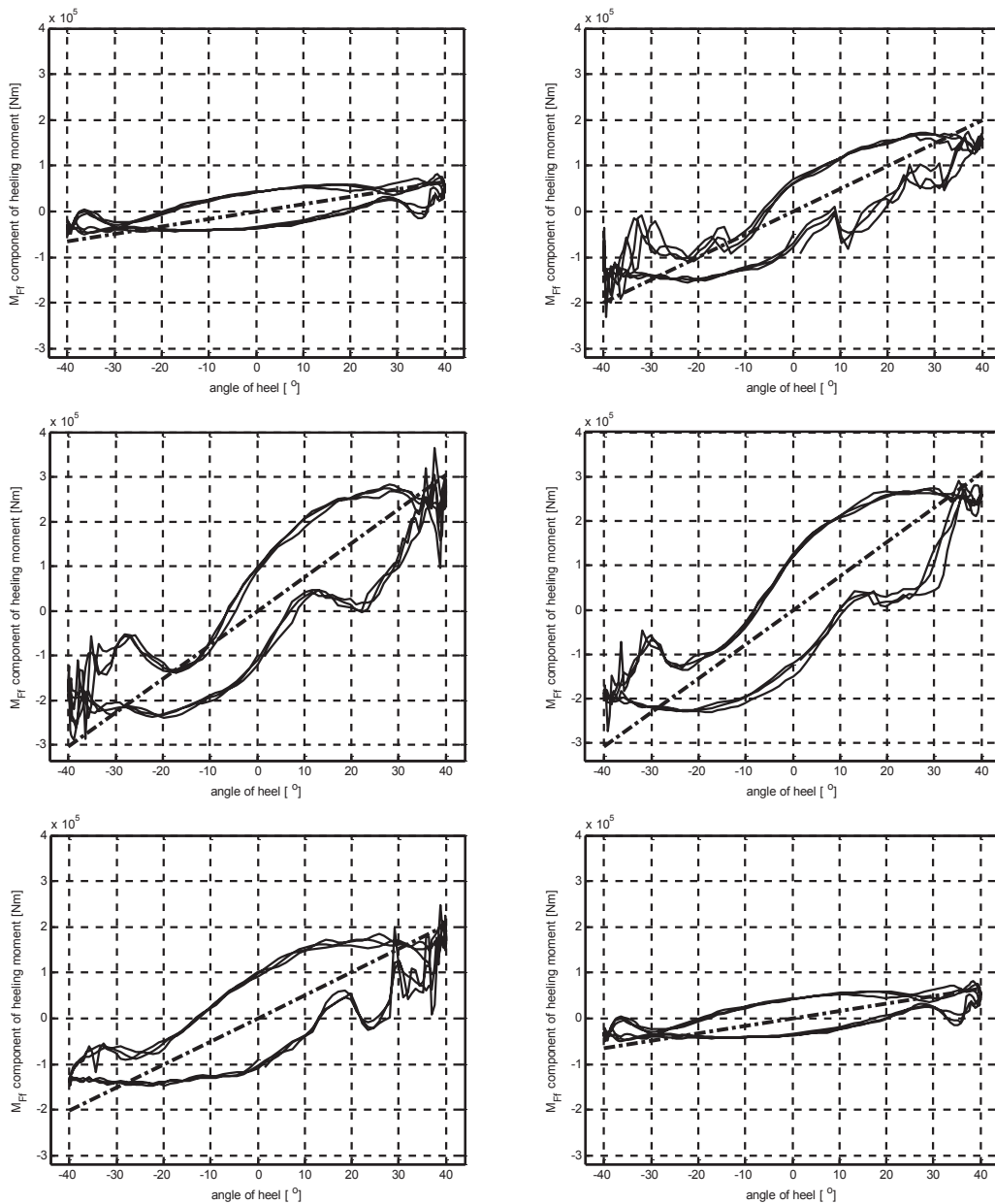

Fig. 10. Linearized free floating component of the heeling moment due to liquid sloshing in the model tank – linearization carried out according to the formula (6) (exemplary case)

The conducted research reveals that the linear approximation of the free floating component of the considered heeling moment rises with the increase in tank's filling level up to about half volume of the tank. Then the moment drops with further increase in the filling level of the tank. This characteristic is shown in Fig. 11.
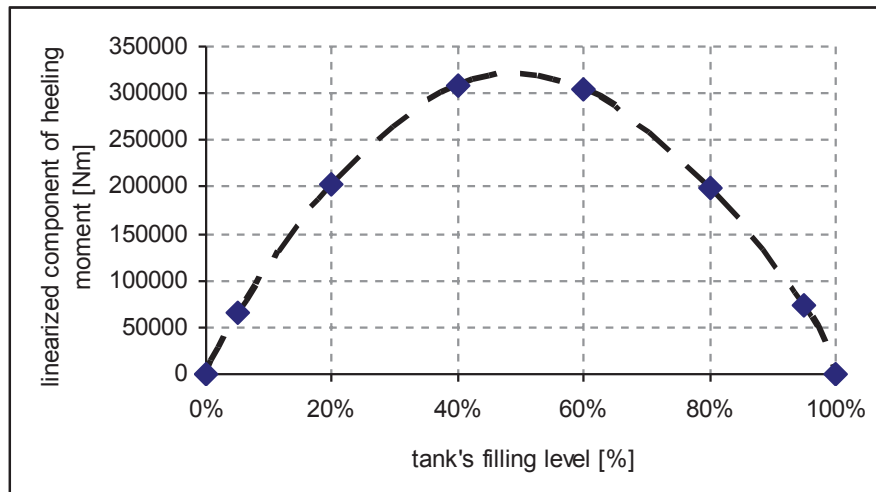

Fig. 11. *Influence of ship's tank filling level on the free floating component of the heeling moment due to liquid sloshing in the considered model tank*

6. Conclusion

The transfer of liquids inside partly filled ships tanks is an essential element of ship stability assessment however it is considered nowadays in a static way only with the use of free surface corrections. The dynamic approach towards liquid sloshing phenomenon, which is proposed in the paper, seems to be profitable because it enables more reliable approximation of ship stability performance. Nevertheless, the studied phenomenon depends on a list of essential variables, thus it cannot be characterized with the use of some simple formulas like in the case of the static approach.

The paper presents the method for computation of the dynamic heeling moment due to liquid sloshing. Thanks to the application of the decomposition concept expressed by the formula (5) and the procedure of moment linearization according to the criterion of equivalent work of the moment, the free floating component of the dynamic heeling moment due to liquid sloshing in ship's tank can be characterized in relatively simple way. Such approach is a worldwide novelty with regard to ships stability application.

The computation carried our for a typical ship's ballast tank reveals that the maximum effect of sloshing liquid is noticed for about half-filled tank. This remark can be a hit while preparing the modified procedure of addressing partly filled tanks problem in the course of ship stability assessment, especially based on the weather criterion.

Acknowledgement

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