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ANALYSIS OF DYNAMIC HEELING MOMENT DUE TO LIQUID SLOSHING IN PARTLY FILLED SHIP'S TANKS FOR REALISTIC RANGE OF ROLLING PERIODS – A CASE STUDY

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Abstract

Liquid sloshing phenomenon is a result of partly filled tank motions. As a tank moves, it supplies energy to induce and sustain a fluid motion. 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. As the ship rolls, the walls of a partly filled tank induce the movement of water. Liquid sloshing phenomenon occurring in partly filled ships tanks directly affects the stability of the 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 and assessment. Since previous researches reveal the necessity of dynamic approach towards liquid movement onboard ships, the investigation is focused on problems related to time dependent wave-type phenomena. This aspect is omitted in the course of standard ship stability calculations. The set of numerical simulations of liquid sloshing taking place in moving tanks is carried out. Among many obtained characteristics, the heeling moment due to sloshing is emphasized and thoroughly investigated. The realistic range of possible metacentric heights and rolling periods is examined. The influence of ship's rolling period on the heeling moment due to liquid sloshing is analyzed for one exemplary seagoing vessel as a case study. However, the conclusions can be generalized to some degree and comprise many other ships.

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

1. Introduction

Ship stability performance depends on two main factors – a shape of her hull and a weights distribution. The first one is a constant value in short and moderate term and can be changed very rarely during a rebuild of a vessel. However, the weights distribution changes in every port in the course of cargo operations and bunkering and related to both of them ballast operations.

The particular sort of changes in weight distribution onboard is liquid sloshing taking place in partly filled tanks. Moving masses need to be avoided onboard however it is impossible to evade them at all. The cargo securing procedures ensure a lack of loose cargo onboard but some free surfaces of liquids in ships' tanks are inevitable. The crucial group of tanks onboard ships, which may be partly filled, are ballast tanks. The problem of an assessment of liquid sloshing effect is nowadays more important then ever because of the obligatory ballast water management requirement. The most common way of maintaining ballast water clean and safe for the overseas environment is exchanging it during a voyage of a vessel. This operation can be dangerous to the vessel and the fair example of such a danger may be the capsizing of *M/V Cougar Ace*. She lost the stability during ballast water exchanging operation tilting significantly on heavy swell that resulted in shifting the cargo and finally laying on the port side [4].

The standard stability calculations carried out onboard include the presence of water in motion. Nevertheless, all the calculations performed according to the IMO Intact Stability Code are static only. The free surface correction is computed and then the righting arm curve is corrected for the negative effect of liquids transfer. Although the recommended by IMO static methods for free surface correction calculation do not take into account many important parameters influencing a heeling moment due to liquid sloshing. Generally, the significant parameters are size of a tank, its height to width ratio, location of a partly filled tank, ship's rolling amplitude and a rolling period. The last one is considered in this paper based on a case study.

2. Loading conditions of a cargo vessel in terms of her rolling period – a case study

The liquid sloshing taking place in partly filled ship's tank was simulated and analyzed for an exemplary cargo vessel. The ship taken for the study is Polish semi-container vessel project B-354. The particulars of the vessel are following:
- length L=140 m,
- breadth B=22 m,
- summer draft displacement D=20767 t,
- summer draft d=9.14 m.

The ship is rather flexible in term of cargo carriage and she can be loaded by break bulk, containers and even a bit of liquid cargo, for instance a pulp. Thus, the great number of typical loading condition is presented in her stability booklet. The general view of the B-354 ship is shown in Fig. 1.

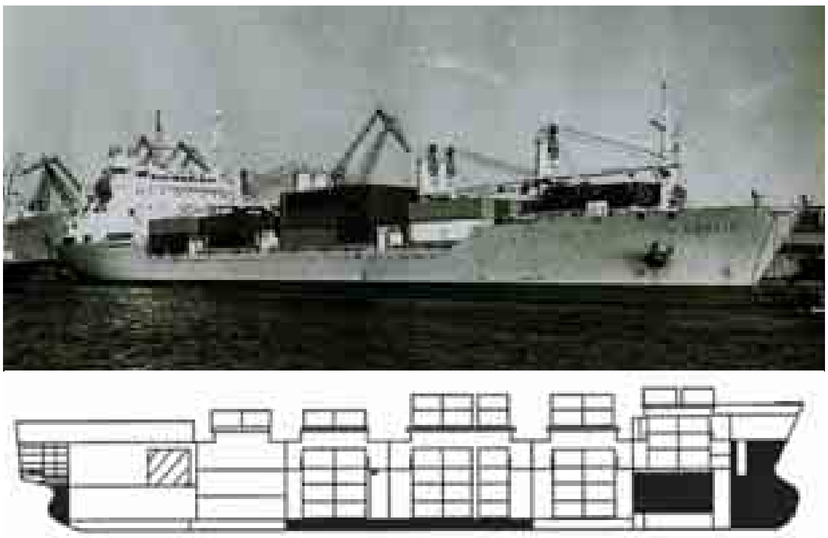

Fig. 1. Ship project B-354 (photo: http://www.plo.com.pl)

For the purpose of modelling of various aspects of the considered ship stability performance the digital model of her hull was worked out. This approach is not obligatory in the course of a research dealing with ship's tank only but it is convenient to have such a complex model for an estimation of any stability-related characteristics. The outer shell of the model is presented in Fig. 2.

Further step of the analysis was an examination of a metacentric height of the vessel in her typical loading conditions. More than thirty of them were investigated and the histogram presenting GM frequency was prepared (Fig. 3).

The consideration of the transverse metacentric height is crucial from the purpose of the paper point of view because of the direct influence of the GM value on the rolling period of the vessel. The values of the metacentric height range from 0.25 to 0.75 m with the share about 60%. The rough estimation reveals the average and predominating GM value equals about 0.5 m.

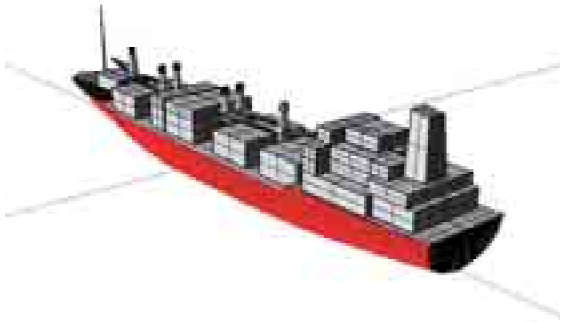

Fig. 2. Digital model of the ship B-354

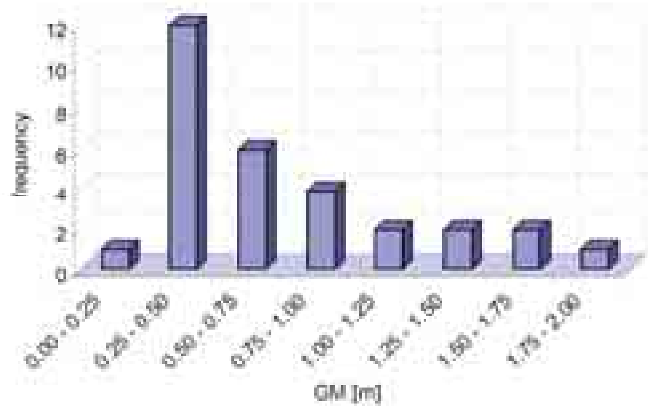

Fig. 3. Histogram of the metacentric height of the ship B-354 in typical loading conditions (according to the stability booklet)

The metacentric height is a main parameter varying ship's rolling period and thus the period of excitation of liquids motion in tanks. The natural period of roll may be obtained according to the formula:

$$T_{\varphi} = \frac{2 \cdot \pi \cdot f}{\sqrt{g \cdot GM}} \approx \frac{2 \cdot f}{\sqrt{GM}}, \tag{1}$$

where:
T_{φ} – natural period of ship's roll,
f – transverse gyration radius of a ship,
g – gravity acceleration,
GM – ship's transverse metacentric height.

As the value of transverse gyration radius of a ship is usually not available on board the simplified empirical formula recommended by IMO (International Maritime Organization) is in common use [2]:

$$T_{\varphi} = \frac{2 \cdot c \cdot B}{\sqrt{GM}}, \tag{2}$$

with the value of c coefficient:

$$c = 0.373 + 0.023 \cdot \frac{B}{d} - 0.043 \cdot \frac{L}{100}, \tag{3}$$

where:
c – coefficient describing ships transverse gyration radius,
B – ship's breadth,
d – mean ship's draft,
L – length between perpendiculars.

The resultant rolling periods, which were calculated for a wide variety of typical loading conditions of the ship, are shown in the form of a histogram in Fig. 4.

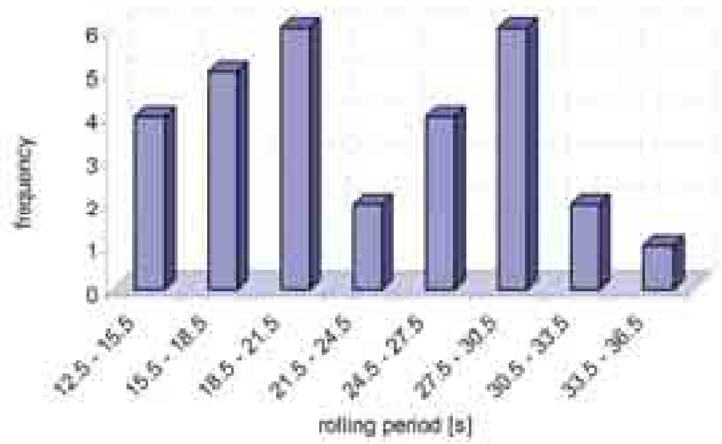

Fig. 4. Histogram of the rolling periods of the ship B-354 in typical loading conditions

The bar pattern in the metacentric height histogram suggests the bimodal distribution of the considered parameter. The first predominant value of the rolling period equals about 17.4 s and the second predominant GM value reaches about 28.2 s. One may state that in the light of the figures the range of researched rolling periods of the B-354 ship should at least slightly exceed the range 17.4 to 28.2 seconds. The authors decided to comprise in the study rolling periods from 14 to 32 seconds covering the typical range of the metacentric heights.

3. Computation of heeling moment due to liquid sloshing in ship's tank

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 most typical rectangular ship ballast tank. The size and location of the tank correspond with its common location in a double bottom of a ship, the rolling period was variable according to the research assumptions and the range of angular motion reflects the very heavy sea conditions in extremely stormy weather, which is presented in the Fig. 5.

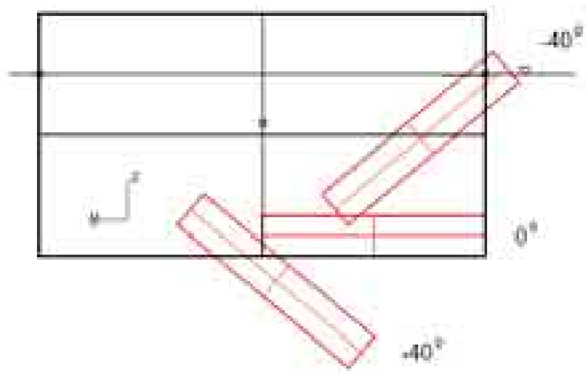

Fig. 5. Geometry of the considered tank and its angular motion

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 that are shown in Fig. 6. The Sub-Grid Geometry Resolution (SGGR) was applied where the triangulated surfaces naturally cut Cartesian cells and reconstructing the free surface [1].

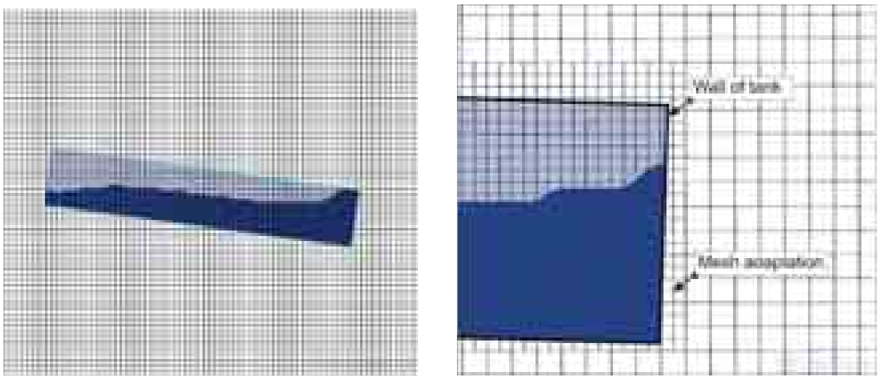

Fig. 6. Mesh applied for CDF calculations

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, which is shown in Fig. 7. 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 [1].

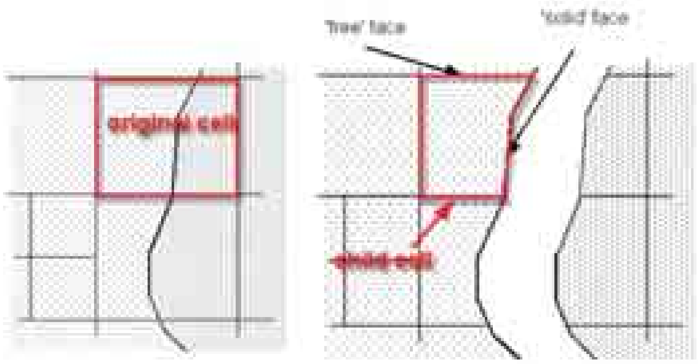

Fig. 7. Sub-grid resolution of curvilinear wall [1]

The *FlowVision* code is based on the finite volume method (FVM) and uses the VOF method for free surface problems that is presented in Fig. 8 [1].

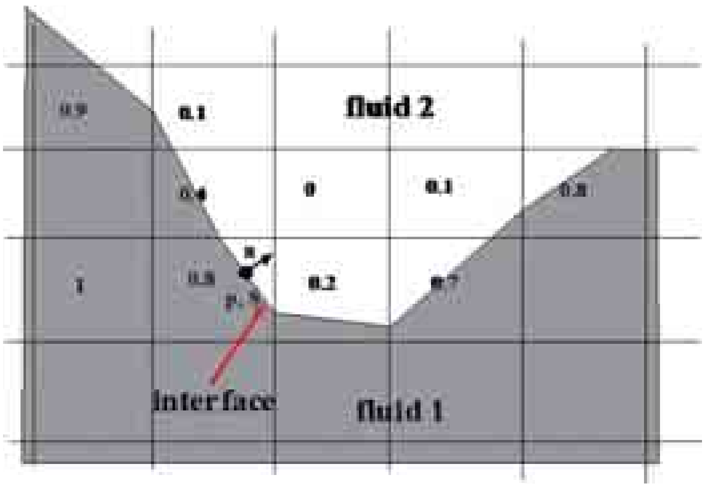

Fig. 8. VOF (Volume Of Fluid) variable is the volume fraction of fluid 1 in a cell, VOF=1 - the cell contains only fluid 1, VOF=0 - the cell contains only fluid 2, 0<VOF<1 the cell contains fluid 1 and fluid 2 [1]

High accuracy of computation is achieved by solving the governing equations in the 'free surface' cells (the cells partly filled with liquid) [1]. 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.

4. Influence of ship's rolling period on heeling moment due to liquid sloshing

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. The exemplary results of the CFD simulation are shown in Fig. 9.

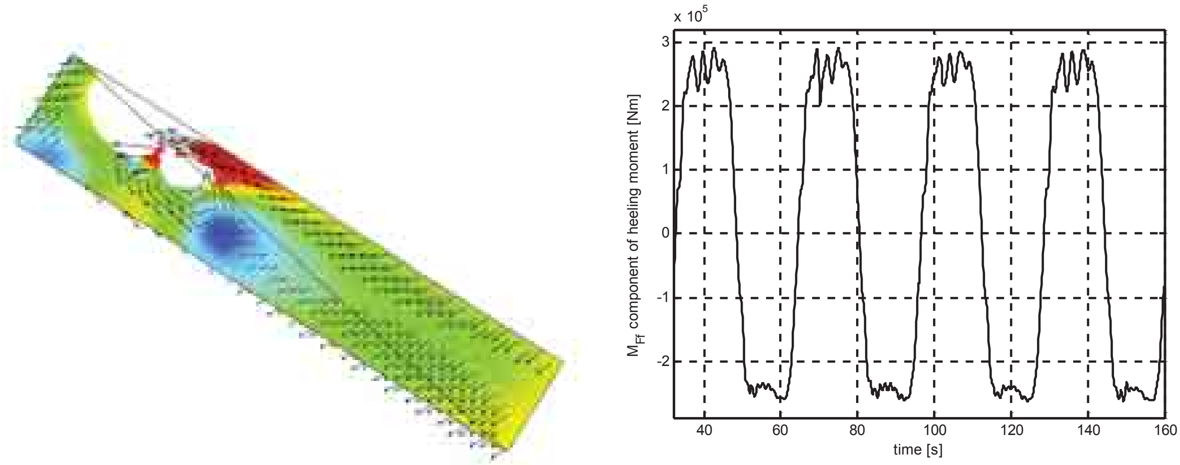

Fig. 9. Results of CFD computation – velocity field and vectors (left) and a history of heeling moment due to liquid sloshing in the considered tank (right)

The obtained heeling moment 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. 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:

$$M_{Total\_dyn} = M_{FL\_dyn} + M_{Ff}\,, \tag{1}$$

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.

Although the heeling moment was computed by 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 proposed decomposition of the heeling moment (formula 1), 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 [3]. The linearization formula can be concisely shown in following notation:

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

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.

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.

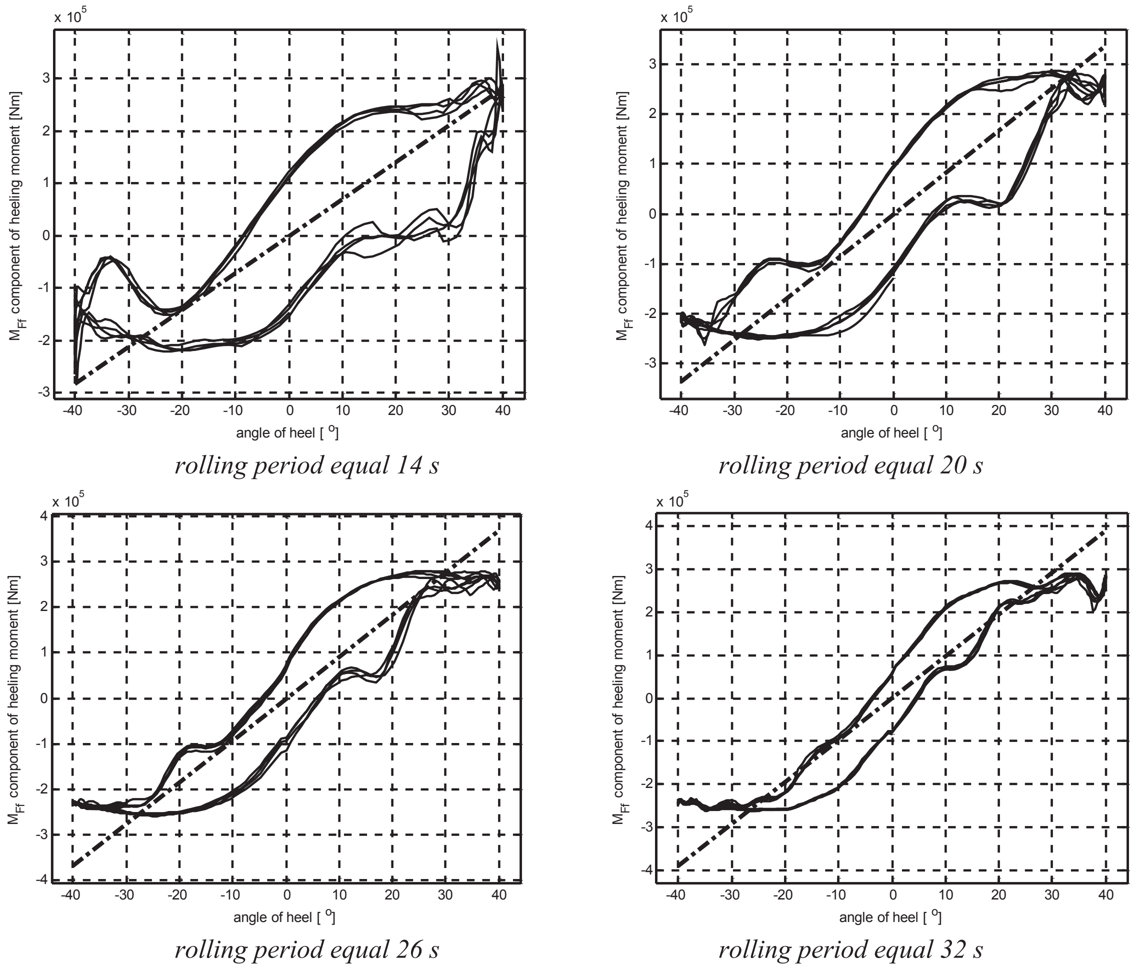

Fig. 10. Linearized free floating component of the heeling moment due to liquid sloshing in the model tank – linearization carried out according to the formula (2)

The characteristic of an influence of the ship's rolling period onto the free-floating component of the heeling moment due to liquid sloshing is shown in Fig. 11.

6. Conclusion

The influence of the ship's rolling period onto the heeling moment due to liquid sloshing in a tank was assessed. The case study comprises the realistic range of the metacentric heights and resulting from them the rolling period of a cargo vessel B-354. However only one typical tank located in a double bottom filled up to the 50% level was analyzed.

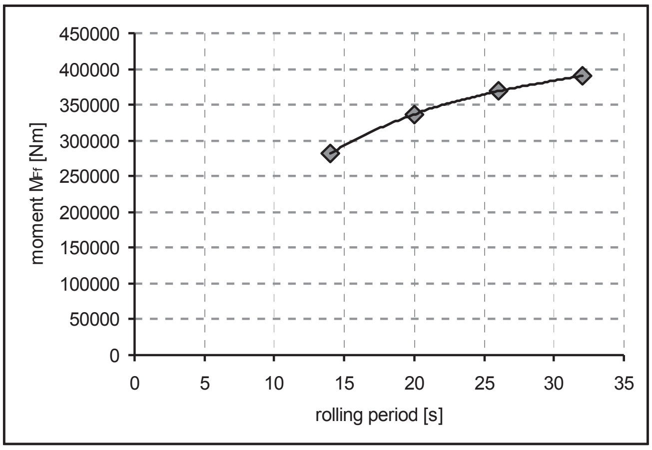

Fig. 11. Influence of ship's tank filling level on the free-floating component of the heeling moment due to liquid sloshing in the considered model tank

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

The conducted research reveals that the linear approximation of the free-floating component of the considered heeling moment due to liquid sloshing gradually rises with the increase in ship's rolling period, however the rate of the rise is dropping. The future prospective for the continuation of the research is to examine other locations of ship's tanks, especially wing tanks.

Acknowledgement

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