# 3D CDF MODELING OF SHIP'S HEELING MOMENT DUE TO LIQUID SLOSHING IN TANKS – A CASE STUDY

**Przemysław Krata, Jacek Jachowski**

*Gdynia Maritime University, Department of Ship Operation*
*Jana Pawła II Av. 3, 81-345 Gdynia, Poland*
*tel.: +48 58 6901144, +48 58 6901134, fax: +48 58 6901101*
*e-mail: inhalt@klif.am.gdynia.pl, jjachowski@o2.pl*

***Abstract***

*Modeling of liquid sloshing inside partly filled ships' tanks can be carried out by a variety of methods. The simplest and perhaps the less reliable is a quasi-static approach which is, however, recommended in the Intact Stability Code by the International Maritime Organization. Hence the only advantage of the static estimation of liquid sloshing is simplicity of calculations, the research into the application of CFD (Computational Fluid Dynamics) was performed in Department of Ship Operation at Gdynia Maritime University.*

*The paper presents results of numerical simulations of a liquid sloshing phenomenon performed by means of a code Fluent. The research was focused on a computation of the heeling moment affecting stability of a vessel, especially on the dynamic effects, which are omitted in obligatory intact ship's stability regulations nowadays. The computed distributions of dynamic pressures on tank walls were carried out for large oscillation amplitude which is characteristic for stormy sea conditions. All the simulations were computed in 3D mode and they provide high accuracy results.*

*A case study described in the paper enables realistic comparison of the results of CFD liquid sloshing simulations and the simple statics-based computations. The study reveals some weaknesses of the contemporary quasi-static approach towards the free surface effect and it might be the contribution to the more sophisticated estimation of the ship's stability than it is achieved nowadays.*

***Keywords:*** *CFD, safety against capsizing, ship's stability, liquid sloshing, free surface effect*

## 1. Introduction

The dynamic behaviour of a vessel at sea is 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 energy to induce and sustain the fluid motion [1]. Both the liquid motion and its effects are called sloshing. The interaction between ship's structure and tank's and water sloshing inside a tank consists in constant transmission of energy. As a ship rolls, the walls of a partly filled tank induce the movement of water.

In such an attitude ship's seakeeping behaviour 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. From the practical point of view the ship's feature enabling withstanding the heeling moments due to wind, waves and internal reasons (for instance liquid sloshing) is called ship stability.

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 her capsizing. Contrary to such state, the excessive stability causes high values of mass forces acting on cargoes and machineries due to strong accelerations.

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 [5].

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 [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),
- 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. The static attitude towards liquid sloshing modeling seems to be too archaic nowadays, thus a research program was performed in Ship Operation Department at the Gdynia Maritime University.

## 2. Case study assumptions – tanks layout of a bulk carrier

The research carried out was focused on dynamic effects of sloshing phenomenon influencing stability of a ship. A case study method was applied, therefore one type of a vessel was selected and all further computations were performed for this ship.

The chosen ship was a general purpose handy-size bulk carrier equipped with double bottom tanks and top tanks (wing tanks). The particulars of the bulk carrier taken into consideration in the course of a case study are as follows:

- length between perpendiculars $L_{BP}$ = 134 m,
- breadth $B$ = 21.4 m,
- displacement in analysed loading conditions $D$ = 16602 t,
- mean draught $d$ = 7.60 m,
- vertical centre of gravity $VCG$ = 7.82 m,
- metacentric height $GM$ = 1.56 m.

The shape and dimensions of typical tanks which were taken for computations in the course of numerical simulations of sloshing phenomenon and analytical calculations, are shown in Fig. 1. They exactly mach the tanks of the selected vessel, moreover they reflect two typical groups of tanks frequently put up in bulk carriers construction.

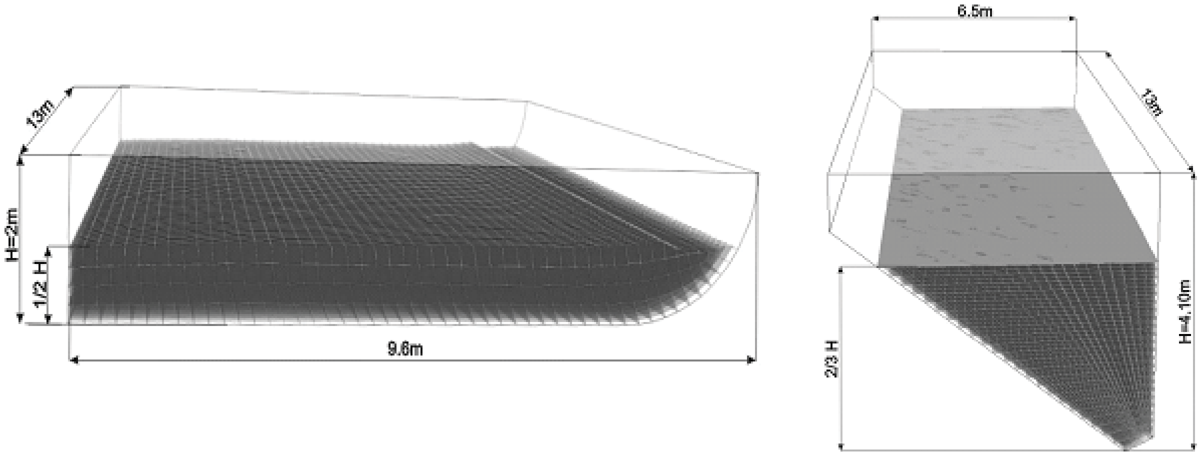


*Fig. 1. Shapes and dimensions of bottom and top tanks of a bulk carrier*

The tanks were considered as partly filled with ballast water and forced to the oscillations. Some particulars of water inside the tanks are given in the Tab. 1.

*Tab. 1. Particulars of tanks partly filled with ballast water*

| location of tanks | filling level | weight of water (both sides) | moment of inertia of free surface of water (one side) |
|---|---|---|---|
| top | $\frac{1}{2}H$ (*) | 155.5 t | 61.8 $m^4$ |
| bottom | $\frac{2}{3}H$ (*) | 212.5 t | 879.8 $m^4$ |
| (*) $H$ - height of each tank | | | |

Apart from the tanks geometry and liquid particulars a set of additional assumptions had to be established. One of the most important issues was the period of ship's roll being the period of forced oscillations of partly filled tanks. It was assumed in the course of the research that the vessel rolls with the period equal to her natural period of roll which 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:
$T_\varphi$ - natural period of ship's roll,
$f$ - transverse gyration radius of a ship,
$g$ - gravity acceleration,
$GM$ - 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 is in common use [5]:

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

$$c = 0{,}373 + 0{,}023 \cdot \frac{B}{d} - 0{,}043 \cdot \frac{L}{100}, \tag{3}$$

where:
$c$ - coefficient describing ships transverse gyration radius,
$B$ - ship's breadth,
$d$ - mean draft,
$L$ - length between perpendiculars,
all remaining symbols like in formula (1).

The formulas (2) and (3) applied to the selected bulk carrier give the value of ship's natural rolling period equal 13 seconds. All numerical simulations of liquid sloshing phenomenon were carried out for such period of tanks' rotary movement.

The last factor considerably influencing the modelled liquid sloshing was angular amplitude of tanks' oscillations. This amplitude was assumed to be equal 40 degrees. It reflects the heavy seas conditions and enables reasoning for stormy conditions at sea [4].

## 3. CFD simulations of liquid sloshing in ship's tanks

The research into the sloshing phenomenon generating ship's heeling moment requires the use of a method for heeling moment calculation. One of the most common approaches nowadays is an application of CFD (Computational Fluid Dynamics).

The 3-dimentional simulations of the sloshing phenomenon were performed by the use of the commercial code "Fluent" which is a universal and flexible tool designed for modeling of liquids dynamics. The version Fluent v.6.3.26 was utilized. The code is based on the finite volume method (FVM), and uses the VOF method for free surface problems [2, 3].

The numerical simulations of the sloshing phenomenon were performed for the oscillation and tank's geometry corresponding with the relevant parameters of the selected bulk carrier described in section 2. All numerical simulations were based on a 3D quadrilateral mesh created in GAMBIT. The computational mesh is shown in Fig. 2.

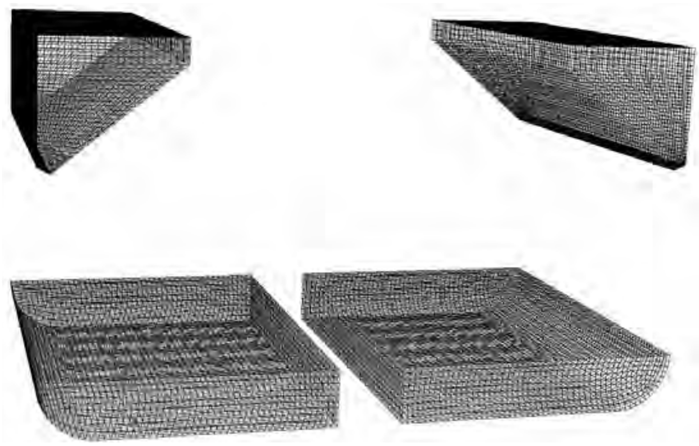

*Fig. 2. Computational mesh applied in 3D simulations performed by Fluent code*

A set of assumptions required for the simulations was applied. Computation time steps of 0.005 s were used in the solution of the conservation equations for mass, momentum, and volume fraction of the liquid. The large-eddy-simulation (LES) approach is adopted to model the turbulence effect by using the Smagorinsky sub-grid scale (SGS) closure model [2, 3]. Furthermore, the VOF model is based on the monovalent assignment of liquid density inside every single computational cell which is presented in Fig. 3.

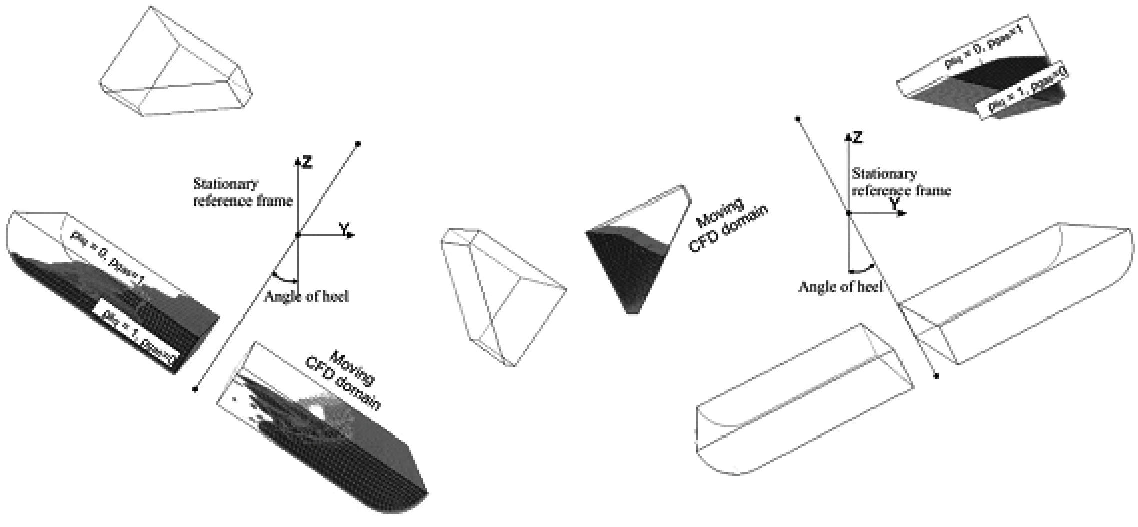


*Fig. 3. Mixture density concept in VOF model and moving mesh formulation for tanks located below and above the axis of ship's roll*

For the sake of reliability of description of considered liquid sloshing phenomenon, the verification process was essential. Such a verification of numerical simulations results was based mainly on two comparative analyses:

- of time history of dynamic pressures;
- of a free surface shape of sloshing liquid.

Both characteristics were recorded in the course of experimental tests [6]. The general inference is that the verification of numerical simulations results were assessed satisfactory in all considered cases and any selected spot in the tank. Thus, all results obtained in the course of numerical modeling were assessed as reliable and qualified for further processing.

## 4. Results and analysis

The final result of numerical simulations of considered phenomenon was heeling moment due to liquid sloshing in tanks, computed in time domain. It was derive as a pressure-by-area integration over all wetted inner surface of the tanks and the moment is shown in Fig. 4.

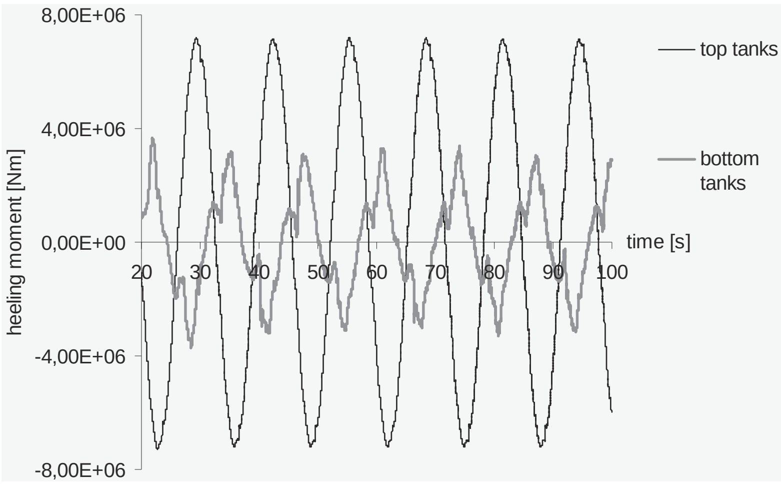


*Fig. 4. Results of numerical simulations – time dependent heeling moment graph*

However the time-domain presentation of results is rather incommodious and the most convenient manner is to plot the values of heeling moment versus an angle of ship's heel. The main disadvantage of such a presentation is the hysteresis loop being the effect of wave type phenomena taking place inside the moving tank. This inconvenience can be removed by the linearization process [7]. As the long-term 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 weather criterion deals with an area under the *GZ* curve, which represents the work of heeling moment, thus the linearization of the researched heeling moment should be based on the work of the moment as well. The work-equivalent method was worked out and applied which is based on the formulas [7]:

$$\begin{aligned} &\int_{0}^{\varphi_{40}} M_{(\varphi)} \cdot d\varphi + \int_{\varphi_{40}}^{0} M_{(\varphi)} \cdot d\varphi = 2\int_{0}^{\varphi_{40}} M_l \cdot d\varphi, \\ &\int_{0}^{\varphi_{40}} M_l \cdot d\varphi = \frac{1}{2} M_{l40} \cdot \varphi_{40}, \end{aligned} \tag{4}$$

where:
$M$ - heeling moment due to sloshing,
$M_l$ - resultant linear heeling moment due to sloshing,
$\varphi$ - angle of ship's heel,
$\varphi_{40}$ - angle of heel equal 40°.

The angle of heel domain plot of heeling moment values and the linear heeling moment due to liquid sloshing is presented in Fig. 5. The linear characteristics of heeling moment comprising

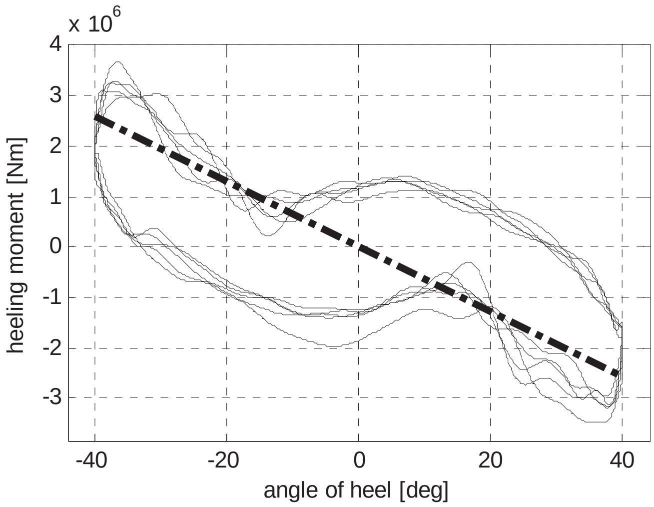


*Fig. 5. Linearization of heeling moment due to liquid sloshing in tanks (exemplary bottom tanks)*

dynamics of liquid movement can by straightforward compared to static moments computed for relevant angles of heel according to the IMO ISC recommendations.

The final stage of the research was a comparison of heeling moments due to liquid sloshing obtained according to different models and approaches. In the course of the analysis the values of linear moment computed by means of 3D numerical simulations with regard to liquid dynamics and nonlinear wave-type phenomena were faced to the results of simple calculations taking into account only statics. As reference values the simple pendulum model was applied which is based on the moment of inertia of liquid's free surface and the model of transfer of liquid's centre of gravity. They both are recommended in the IMO IS Code.

The comparableness of results was achieved by calculation of the virtual rise in VCG of the ship which is standard procedure in the course of on-board stability calculations. The comparison of results is shown in Tab. 2.

*Tab. 2. Virtual rise in VCG due to movement of liquids in partly filled tanks – case study*

| | virtual rise in VCG [m] | | |
|---|---|---|---|
| location of tanks | simple pendulum model | transfer of fluid centre of gravity | dynamic approach |
| top | 0.007 | 0.001 | 0.037 |
| bottom | 0.106 | 0.037 | 0.063 |

The virtual rise in VCG of the considered bulk carrier due to free surface in bottom tanks which was computed with the use of RANS based numerical simulations and post-processed by the linearization, achieves the value in-between the results of simple pendulum modeling and static moment due to transfer of fluid centre of gravity. As the dynamic approach is most reliable one, the simple pendulum model overestimates the influence of liquid movement in slacked tanks and the static moment model underestimates it. However for top tanks (wing tanks) both statics-based methods significantly underestimate the free surface effect, although the performed research did not include the influence of inner structure of tanks' constructions like girders and frames.

## 5. Conclusions

Transverse stability of a vessel is one of the key issues regarding her safety at sea. Liquid sloshing taking place in partly filled tanks affects the stability performance thus it needs to be taken into account in the course of ship's stability assessment. The contemporary methods of free surface effect estimations are based only on the static approach.

The results of the case study reveals that, for wide bottom tanks of the considered bulk carrier, the virtual rise in VCG computed with regard to dynamics of sloshing liquid is placed in-between two results carried out according to the IMO recommendations. The results are significantly different for relatively narrow top tanks located quite far from the axis of ship's roll. The static free surface correction is rather negligible while the inertia of liquid weight generates substantial heeling moment.

The case study contributes to better estimation of an influence of liquid sloshing phenomenon to the stability of vessels. The obtained results could suggest the need for revision of the attitude towards free surface effect calculation and lead to further research programs focusing on this matter. The special attention should be paid on the cases when static methods underestimate the decay of ship's stability hence it is dangerous to the vessel and affects safety of navigation.

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