SHIP'S HEELING MOMENT DUE
TO LIQUID SLOSHING IN TANKS – 3D ATTITUDE

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Abstract

The matter of the paper refers to the dynamic stability of a vessel as an important factor affecting her safety at seaway. 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. Liquid sloshing phenomenon is a result of partly filled tank motions. As a tank moves, it supplies the energy to induce and sustain the fluid motion. The dynamic behaviour of a vessel at seaway is considerably affected by the dynamics of free liquid surfaces, therefore the influence of fluid movement taking place in partly filled tanks on the safety of ship's exploitation process is emphasized.

The paper presents the results of the experimental research and the numerical simulation of the sloshing phenomenon. The research was focused on the computation of the heeling moment affecting the stability of a vessel, especially dynamic effects, which are omitted in obligatory intact ship's stability regulations nowadays.

The experiment performed in the course of the research was carried out in Department of Ship Operation at Gdynia Maritime University. The unique test apparatus was designed and built. It enables to measure dynamic pressures on model tank walls for large oscillation amplitudes, which are characteristic for stormy sea conditions. The numerical simulations of liquid sloshing phenomenon, took into account the viscosity of liquid and the turbulence of considered flows. All the simulations were computed in 3D mode and they provide high accuracy results.

The spatial distribution of dynamic pressures on model tank walls enables computation of heeling moment due to liquid sloshing which affects ship's stability. Further analysis of obtained moments was carried out. The study may be the contribution to the more sophisticated estimation of the ship's stability than it is achieved nowadays.

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

1. Introduction

Safety of navigation or widely comprehended safety of a vessel at seaway is nowadays considered from many points of view. 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. Stability against capsizing in heavy seas is one of the most fundamental requirements considered by naval architects when designing a ship [3]. The need for researching capsizing or heeling mechanics is to model a vessel's behaviour in extreme seas and to relate this to her geometric and operational characteristics to gain cost effective and safe operation [3].

Capsizing is a phenomenon not often occurring at sea, although it brings about a considerable number of fatalities, especially with regard to relatively small vessels [11]. Thus, any research aiming at the stability of vessels seems to be essential regarding the safety of sea transportation.

There are many causes for stability accidents and they can be divided into several typical groups, as shown in Fig. 1.
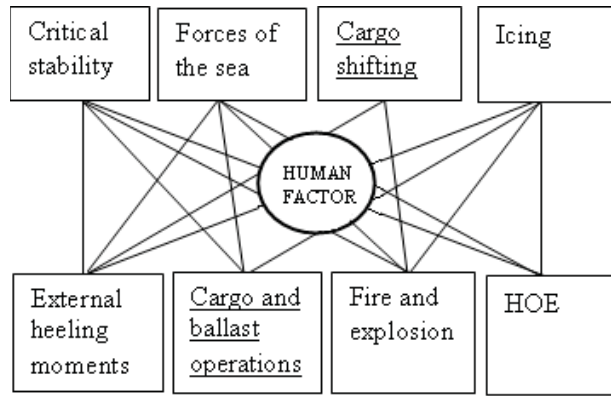
Fig. 1. Hazards to stability [8]

Cargo shifting incidences and some accidents related to cargo and ballast operations may be connected with or involved by sloshing of liquids in partly filled tanks on board of seagoing ships, which usually restricts stability of a vessel. On the other hand, the considered sloshing of liquids may reduce in some cases a ship's rolling amplitude and soften her movement [5], [12]. The dynamic behaviour of a vessel at sea may be considerably affected by the dynamics of the free liquid surface and it is essential with regard to the safety of a vessel at seaway, human's life and environment [7]. Therefore the research into the sloshing phenomenon was carried out in Ship Operation Department of Gdynia Maritime University.

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 [1]. 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. The mass and the energy are conserved within the cycle. The basic measurable effect of a sloshing phenomenon is a dynamic pressure occurring on walls of a partly filled tank. The distribution of the pressure can be obtained mainly by two methods, experimentally or in the course of a numerical simulation.

2. Experimental investigation into the sloshing phenomenon

The experimental tests performed at Gdynia Maritime University enabled measurements of dynamic pressure distributions on the side wall of a model tank and in its upper corner [10]. The experimental investigation on a pressure distribution due to sloshing required arousing of a sloshing phenomenon. After that, the dynamic pressure time history in selected spots was measured and recorded. To achieve this, a test apparatus was designed and built [10].

The main part of the apparatus is a tank. It is equipped with pressure transducers and an inclinometer. The tank is forced to oscillating movement that excites the water movement inside it. The dimensions of the model tank are breadth $b_z = 1,040$m, length $l = 0,380$m, depth $H = 0,505$m. The tank is hanged on the shaft and forced to the oscillation by a drive mechanism. The view of the testing apparatus is shown in Fig. 2.

The experimental research into the pressure distribution due to sloshing was performed for a variety of external excitation parameters. The period of the oscillation varied from T=2,6 s to T=6,5 s. The amplitude of the tank's rotary motion during the model tests and simulation was assumed equal 40°. It reflects the heavy sea conditions and enables to draw conclusions for the worst possible condition at sea [5]. The tank filling level was assumed to be 30%, 60% and 90%. The lever *os*, as the distance between the centre of the tank and the rotary motion axis, was changed from *os*=-0,718 m to *os*=0,718 m. The positive value of *os* describes the tank's location beneath the shaft (modelling the rolling axis) and the negative value of *os* describes the tank's location above the shaft.
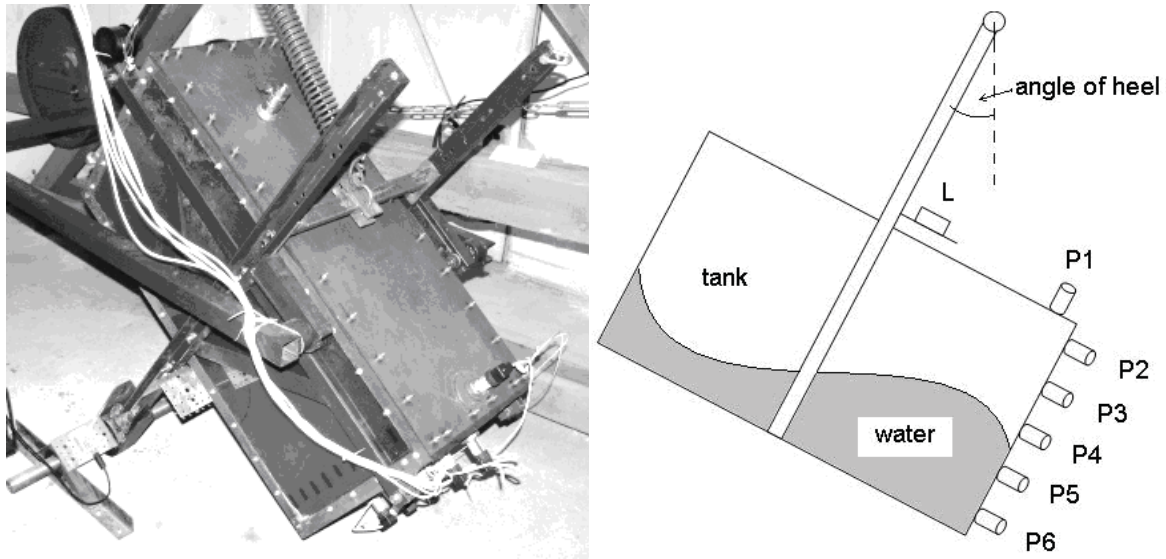
Fig. 2. The experimental setup

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 a result of the global movement of liquid in the tank and it affects the transverse stability of the ship.

The analog signals received from the sensors were sampled and transformed into discrete digital signals by the 12-bit A/D card and then they were recorded. The maximum working frequency of the measuring device was 1000 Hz. Thus, the aliasing distortions of the measured signal were avoided, because the measuring instruments were much faster than the required Nyquist rate for the sloshing phenomenon. The further digital signal processing was carried out. The main operation was low pass filtering for high frequency noise reduction. The filtering enabled to decompose the recorded digital signal and emerged the non-impulsive dynamic pressure component.

3. Numerical simulation of liquid sloshing inside ship's tank

The pressure distributions obtained in the course of the experimental investigation were supplemented by the results of numerical simulations. The 3-dimentional simulations of the sloshing phenomenon were performed by the use of the commercial code "Fluent" which is an universal and flexible tool designed for modelling 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, 4].

The numerical simulations of the sloshing phenomenon were performed for the oscillation and tank's geometry corresponding with the relevant parameters of the experimental investigation. The height of the water level varied from 30% to 90% of the maximum tank's height. All numerical simulations were based on a 3D quadrilateral mesh consisting of 30,000 cells, which was created in GAMBIT. The computational mesh is shown in Fig. 3.

A roll of assumptions required for the simulations was applied. Computation time steps of 0.005s 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, 4]. Furthermore the VOF model is based on the monovalent assignment of liquid density inside every single computational cell which is shown in Fig. 4.
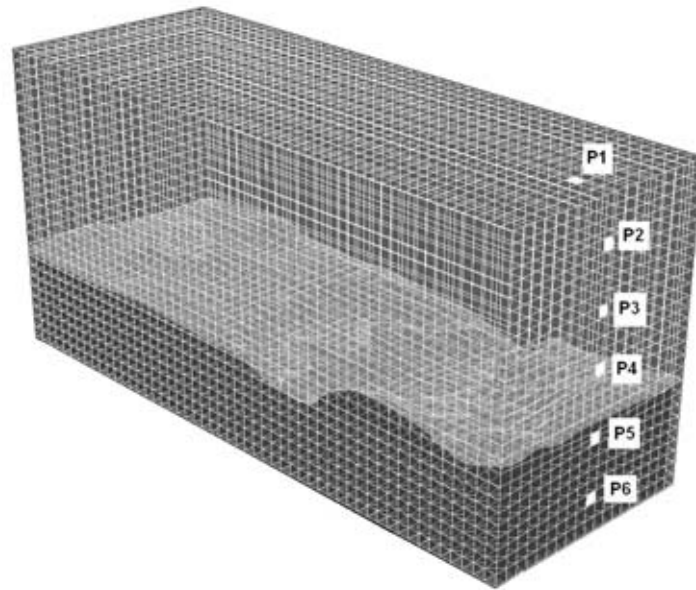
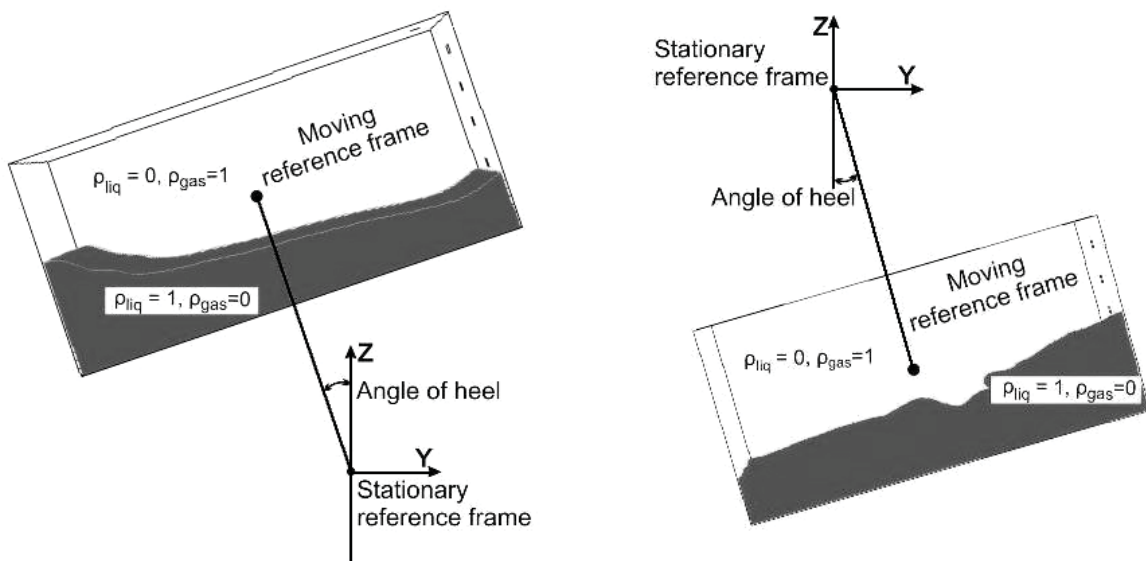*Fig. 3. Computational mash and location of virtual pressure gauges*

Fig. 4. Illustration of mixture density concept in VOF model and moving mesh formulation for tank located below and above the axis of ship's roll

Tank rotary motion, corresponding to the motion of physical model tank used in the course of the experimental tests, was implemented to "Fluent" by the use of a user-defined function (UDF). A stationary reference frame and a moving reference frame were defined, as shown in Fig. 4 for both considered cases of tank location (below and above the rolling axis).

A verification of numerical simulations results was based mainly on the comparative analysis of time history of dynamic pressures recorded in the course of the experimental tests and computed ones. The comparison reveals fair conformability, which is shown in Fig. 5 for one exemplary case and one pressure gauge. The general inference is that the higher elevation of liquid surface over the pressure gauge, the better conformability of simulations results and measurements is noticed. However, the verification of numerical simulations results were assessed satisfactory in all considered cases and any selected spot in the tank.
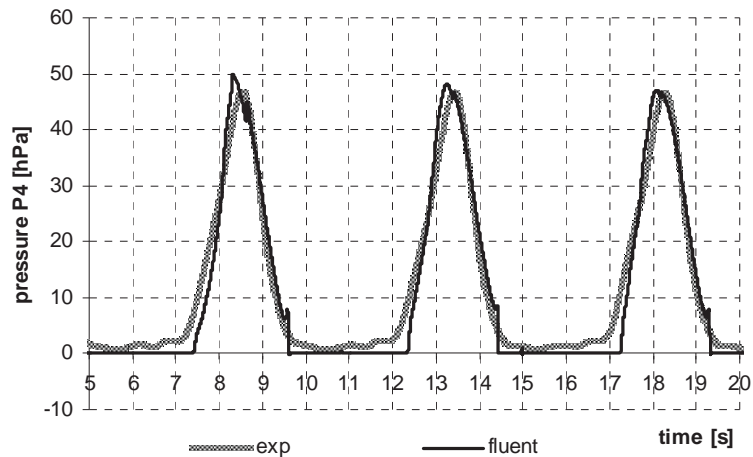
Fig. 5. Time history of dynamic pressure due to liquid sloshing (an example for the pressure gauge P4 – see Fig. 3)

Another comparative analysis performed as an additional step of verification of numerical simulations results was applied to the shape of free surface of sloshing liquid. The experimental tests were recorded and screenshots from the movies were compared to the relevant steps of animations generated in the course of the simulations. The phase of the tank rolling cycle was obviously complied in all compared cases. An example of the comparison of free surface shapes is shown in Fig. 6.
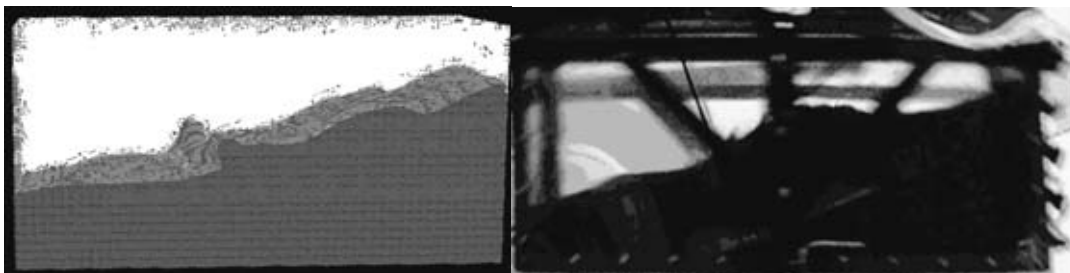

Fig. 6.   General flow patterns: "Fluent" results (left) are compared to a photograph taken at the same time within an oscillation cycle (right)

Aside from the computed 3-D pressure distribution, the additional information about the spatial arrangement of liquid particles velocity vectors was obtained. The visualization of velocity vectors is shown in Fig. 7, which is expedient with regard to the further reasoning about any discrepancies between quasi static attitude towards liquid sloshing phenomenon which is currently required by the IMO IS-Code [6] and the 3-D dynamic solution obtained in the course of the research [9].
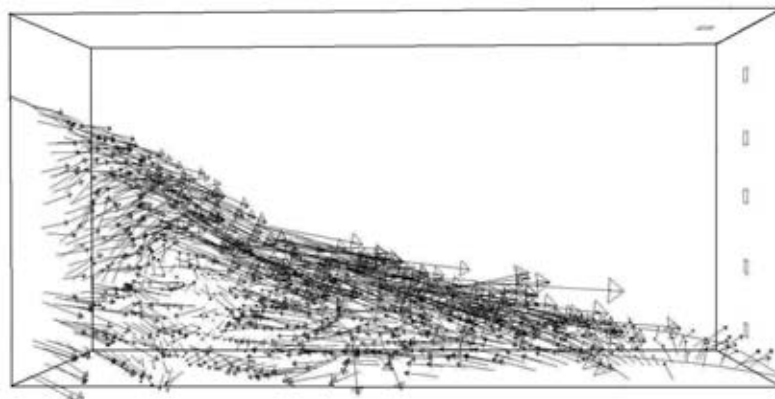

Fig. 7. Velocity vectors of liquid sloshing in a tank

4. Results of the research

The positive verification of the results of numerical simulations carried out with the use of "Fluent" code enabled the next stage of the research, which is the ship's heeling moment calculation. The heeling moment due to liquid sloshing is one of the components of total heeling moment involving motions of ships. The critical movement from the ship's stability point of view is rolling therefore the transverse heeling moment was computed. The general formula for force moment determination may be following:

$$M = \int_S r \times n \cdot p \, ds \, , \tag{1}$$

where:

S - the surface of the tank's walls,

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.

The dynamic pressure spatial distribution was obtained for every single time-step in the course of the numerical simulations. The tank surface area, the position vector of every spot and the normal vector result solely from the tank's geometry and its location within established reference frame. Thus the heeling moment M described by the formula (1) may be obtained by simple numerical integration performed for main directions on the basis of tank's walls projections. An example of resultant heeling moment is shown in Fig. 8.
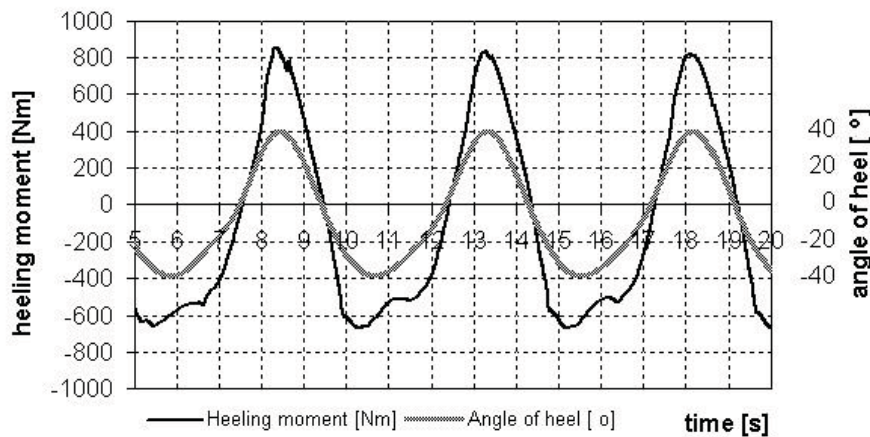

Fig. 8. Heeling moment due to liquid sloshing and angle of heel versus time

The graph shown in Fig. 8 presents the heeling moment M due to liquid sloshing versus time and angle of heel versus time as additional information. The coincidence of phases of a heeling moment and an angle of heel is different for various tank locations referred to the axis of roll [9].

5. Conclusion

The movement of liquids in partly filled tanks affects ships' stability and, therefore, it is taken into account in the course of the stability assessment procedure in accordance with the IMO IS-Code recommendations [6]. The research presented in the paper reveals that 3-D nonlinear computation can be applied to the sloshing problem. The novelty of the research is mainly the large amplitude of tank rotary movement and considered characteristics of rolling. Most published studies in the scope of the subject presents the results of experiments and simulations for small excitation amplitudes (about 4 to 8 degrees) and rolling periods close to the natural period of liquid movement inside a tank [9]. Such an attitude is useful for the purpose of strength calculation

which is the main field of interest with regard to the sloshing phenomenon. The research presented in the paper is focused on the stability effects of liquid sloshing therefore the period of roll had to be longer but concurrently the angular amplitude had to be larger (the rolling amplitude was assumed 40 degrees in the research). Such a range of excitation parameters contributes an unique set of results of liquid sloshing numerical simulations.

The positive experimental verification of the numerical simulations results avers the usefulness of VOF method applied in "Fluent" code for liquid sloshing problem simulation for large ship's rolling amplitudes. The set of admitted assumptions regarding the application of VOF method and the large-eddy-simulation (LES) adopted to model a turbulence effect by using the Smagorinsky sub-grid scale (SGS) closure model was valid and effective.

The performed verification reveals good conformability of simulation results with experimental data in terms of a period, an amplitude, and the overall trends. The verification was based on the time history of a pressure distribution at the tank walls and a shape of a liquid free surface. This conclusion enables undertaking the next stage of the research comprising parametric analyses of variables influencing the sloshing phenomenon on board ships.

6. References

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