Interaction between motion of free fluid surfaces and ship motions

D Lamba¹, A Duse², C Varsami³ and R Hanzu-Pazara⁴
¹,²,³,⁴Constanta Maritime University, Navigation Department,
104 Mircea cel Batran Street, Constanta, Romania
E-mail: hanzu@imc.ro

Abstract. This scientific research presents very important aspects of the liquefying process of bulk cargo carried on board merchant ship which may lead to loss of the intact stability of bulk carriers, with serious consequences for the safety of ships and their crew.

We are going to present an analytical modelling, modal analysis and finite elements analysis applied in the hydrodynamics of the ship in the water environment, when realising a complex model 3D of the ship’s bulkheads by modelling with finite volumes with the purpose of emphasising these walls’ behaviour when on board the bulk carrier there is a sloshing effect due to free liquid surfaces in the ship’s cargo holds and we also performed a complex study regarding the structural answer of transverse bulkheads of the cargo holds due to the impact of free liquid surfaces.

1. Introduction

In the last years, an increased number of ships lost their intact stability due to cargo liquefying. Some of them developed large listing angles while others, unfortunately, capsized.

Besides the practical methods for evaluation on board ships of the possible liquefying state of bulk cargo, recommended by the International Maritime Codes for cargo transportation, regulating carriage of cargo, this thesis presents a possible method of determining the listing moment of the ship due to cargo liquefying, and also the possibility of cargo shifting during the liquefying process.

In the field of analysing the „sloshing” phenomenon, there are many papers researching this subject especially in the maritime field. One of the main concerns generated by this phenomenon is the impulse type loading given by the large volumes of liquid flowing from the holds/tanks of the ships over the structure of the ship which may lead to structural deformations over their walls. Such structural deformations due to „sloshing” have been reported especially in case of oil tankers and LNGs.

In the 1950-1960’s experimental studies and analytical ones have been pursued for space ships of the rocket type, and in the 1970-1980’s this issue was addressed in the case of LNGs. Starting with 1980 once the finite elements analysis methods arose, these phenomena started to be studied by researchers.

This paper is meant to continue this trend of involving the finite elements analysis in this damaging phenomenon analysis over the structure of a bulk carrier.

The paper includes experimental research as in numerical simulation of the effect of free liquid surfaces on board – stage 1 – geometrical modelling (CAD) and numerical analysis with Ansys CFX and stage 2 - numerical simulation of the effect of free liquid surfaces on board the ship, resulting in
three different scenarios. In establishing the parameters used for the simulation, the fact that during the sloshing phenomenon the bulk carrier’s holds are ballasted or loaded at different levels was also considered. Numerical simulation was performed by using the Fluent soft included in Ansys. Results of the experimental simulation emphasised the close relation between the shapes of the free liquid surfaces and the calculated ones, proving the capacity of CFD to accurately simulate the evolution of the sloshing phenomenon in the cargo holds of a bulk carrier and some partial conclusions. CFD (Computed Fluid Dynamics) may be considered precise enough in simulating flow in such a way as to be considered a „Numerical hydrodynamic model” for this paper.

2. Ship to be simulated
Further on we are going to generate the numerical simulation of the effect of on board free liquid surfaces over the stability of a bulk carrier structure. The numerical instrument used will be the interaction between the fluid and the structure. The seawater will act through the waves over the bulk carrier structure, which will act over the cargo that could be a fluid (or assimilated to a fluid) which fluid will react on the cargo holds’ walls (generating the sloshing phenomena). So this type of interaction will govern all the phenomena related to the subject of our research.

The ship chosen for our research is a bulk carrier with the following characteristics:

- Length = 290 m
- Beam = 32 m
- Draft = 11.1 m
- Deadweight = 57.700 tdw
- Engine MAN B&W 6S50MC = 8.200 kW
- Thickness of the steel plate = 22 mm.

The image of this bulk carrier was generated by using SolidWorks 2014 generating the geometrical CAD model of the bulk carrier presented in figure 1.

![Figure 1. CAD geometrical model and plan of the bulk carrier chosen for study.](image)

We should mention first of all that the numerical simulation which comes next involves a high degree of complexity needing substantial calculus results on the computer level; therefore the symmetry property of the bulk carrier should be used numerically modelling only half of the ship in order to save resources.

CFX resulted model is given in the figure below:
Three monitoring points are distinguished measuring the movement of the entire network of finite volumes on the vertical (axis Oz):

- WaveHeight is ahead of the ship’s stern measuring the height of the wave generated by the mobile wall.
- Bowpt monitors the vertical movement of a point on at the stern of the bulk carrier.
- COMpt monitors the vertical movement of the Mass Centre of the ship’s keel.

Only results corresponding to the final calculus step are presented which is the actual final time $t=10$ seconds $=$ Time step 100.

In the figure above, the fields’ distribution may be observed for pressures of the wave over the ship’s keel, with maximum 5257 Pa at the extreme aft end of the ship.

Speed of water along the bulk carrier’s keel is distributed as shown in the figure above, with a maximum at the bow of 0.25 m/s, with a stagnation area amidships with a slight acceleration towards the stern of the bulk carrier.
Figure 4. Pressure fields’ distribution.

Figure 5. Speed of water along the keel.
Calculated flotation force exercised on the ship’s keel by water is almost uniform with a maximum value of 9766 kg/m²s² taking the shape of the wave on the water-air interface level.

3. Simulations for Scenario 1 - All cargo holds are ballasted 50%
The intention is to analyse transitory phenomena of sloshing for 20 seconds when the gravity centre of the ship makes a complete cycle and for one second 4 calculus points are established.

In this way the transitory simulation shall have 80 calculus points (every 0.25 seconds) in such a way to provide solutions’ stability. If calculus steps are too high, then solutions loose stability and calculus fails. If steps are too low then the calculus effort becomes too intense. Therefore a different decision in the simulation strategy is modelling only the area of the holds generated in SolidWorks, as shown below:
Deliberately, the reinforcement area between the bulkhead and the top tank was omitted, precisely in order to study the effects of the absence of such reinforcement modelling therefore a tension concentrator. There are also (simplified) reinforcements on the longitudinal line, but on a transverse direction, which are rare in order to study the effect of a weak design.

CAD model is obviously simplified lacking the precise modelling of frames because such a model would need a massive calculus effort. Only for information, with 4 micro-processors working in parallel, the CPU time for simulation of ballasted cargo holds was 1020 de minutes (17 hours). For the simulation of an exact geometry we estimate the need of 32 micro-processors.

For all three simulation scenarios the fluid’s behaviour was analysed (CFD) in all five cargo holds. In order to simulate the existence of the fluid only in cargo holds 1-3-5, at the import stage of the pressure distribution from CFX to the structural calculus module, the pressures for cargo holds 2-4 have not been imported and in this way the structural module made the calculi in their absence.

![Figure 8. Finite volumes network at CFD analysis.](image)

The finite elements network for each of the cargo hold area is presented in the figure above. A specific aspect is the fluid’s behaviour in the vicinity of the bulkheads, this area being discredited by inflation in 5 layers in such a way that the pressure’s distribution in this area would be as accurately calculated as possible.

Conditions to the border should provide an Opening type limit on the superior part of the cargo holds as shown in the figure below in order to model the air start above the cargo (or water ballast) and the lateral bulkheads are the definition of „Wall” type borders to function as limits both between the fluid phase and the solid walls of the cargo holds and to be able to receive the movement which is supposed to simulate the movement of the gravity centre of the bulk carrier as it was defined above.

![Figure 9. Border conditions.](image)
The simulation scenarios are:
- Scenario 1 - All cargo holds are ballasted 50%
- Scenario 2 - Cargo holds 1-3-5 contain cargo 50%
- Scenario 3 - Cargo holds 2-4 contain cargo 65%

The results shall be given for the steps for seconds 5, 10, 15 and 20 as the presentation of all results from all 80 simulation steps is impossible. Still for the most important results the scenarios worked as follows.

In this paper we are going to present Scenario 1- All cargo holds are ballasted 50%.
- Evolution of the water-air free surface

Evolution in time of this surface is given by establishing at CFX-Post the variable presentation of water. The volume fraction of water is 0.5 which by definitions limits the area taken by air from that taken by water.

![Figure 10. Evolution of the free surface in time.](image)

It can be observed that the movement of cargo holds according to the law shall make the fluid content to remain inertial behind, which generates disequilibrium in the fluid’s mass generating an internal wave which is actually the sloshing effect.

The total pressure areas (which include also dynamic pressures) may be visualized both in two longitudinal and transverse sections through the cargo holds area but also at the level of bulkheads as seen below:

![Figure 11. Evolution of pressure in time-section – second 20.](image)
Pressure on the top tank due to the weight of water shall follow the evolution of the internal wave with maximum values between $1.4 \times 1.53 \times 10^5$ Pa. On the bulkheads as shown above, pressure shall fluctuate as the internal wave develops pressure on them.

- Density evolution in time
  Density inside cargo holds is given by the different density of air and sea water in such a way that it shall follow the evolution of the internal wave. Shown with blue is the space taken by air with a density of $1.185 \text{ kg/m}^3$, and with red is the water with a density of $997 \text{ kg/m}^3$ as shown in figure 13.

![Figure 12. Evolution of pressure on bulkheads in time-section.](image)

![Figure 13. Evolution of density in time-section.](image)

- Superficial tension force
  Presence of two fluids of gas-liquid type involves the existence of a free surface on which superficial tension forces apply. This tension plays an important part in modelling free surfaces.
As seen in figure 14, in each cargo hold where the free surface has the lower curve the strongest superficial forces vary a lot between 1.2 and 8.1e-4 kg/m2s2, according to the evolution of the internal wave in the hold.

![Figure 14. Superficial tension force evolution in time-section.](image)

- Speed of the internal wave
  The internal wave in its evolution shall have a particular speed. Water has acceleration areas where speed increases and stoppage where the liquid’s impulse is passed to the bulkhead as dynamic pressure. This is in simple terms the sloshing phenomenon. Calculated speed shall vary between 1.1-2.2 m/s.

![Figure 15. Evolution of the ballast water speed in time-section.](image)

- Induces shear tension from the liquid onto the bulkhead
  Shear between liquid and bulkhead appears and shearing tension as shown below:
  Depending on the shear between fluid and bulkhead, the higher the pressure and local movement the lower the shearing tensions with values between 1.2-8 Pa.
  Numerical analysis with Ansys structural Module Scenario 1 - Entry data in simulation CAD entry geometry in structural simulation, obviously, is the same with the one used in CFD simulation. When it comes to the finite elements network, it is presented below, along with the statistic of the number of elements and knots:
Figure 16. Evolution of shearing tension in time – section.

Figure 17. Finite elements network.

Figure 18. Border conditions applied.
When it comes to the border conditions, these are of Pressure type imported by CFD module, Fixed Displacement type which are applied on the top tank and Variable Pressure type applied on the ship’s sides which simulates pressure of sea water on the bulk carrier’s structure, higher towards the bottom (depth) of the sea, and lower towards the sea surface as in the figure below.

- **Total displacement**

  Total displacement sums up all results of displacement on all directions of coordinated axis. Given the large dimension of the modelled area, maximum displacement is 0.058 m at the exterior bulkhead of the cargo hold no. 5 (labelled MAX) which is reasonable at the total length of the area of 150 m. One may notice a blockage phenomenon at the level of cargo holds no. 1 and 5 on the board side, as an effect of the lack of any frame structure well designed. The first recommendation would be (as we established at the beginning) reinforcement of the ship’s boards with supplementary frames.

![Figure 19. Total displacement.](image1)

- **Equivalent elastic deformation**

![Figure 20. Equivalent elastic deformation.](image2)
Another alarm signal is the presence of an equivalent deformation with maximum von Mises of 0.00486 mm at the base of the aft bulkhead of the hold no. 4. As maximum deformation delimits the elastic area for steels from plastic as 0.002 mm this means that the area is strongly deformed. Therefore, as we have previously mentioned, the area (areas) of passage from bulkheads to the ship’s bottom should be reinforced and redesigned for eliminating powerful tensions concentrators.

- Von Mises equivalent tensions

![Figure 21. Equivalent tension.](image1)

One may observe that in the same area of maximum deformation, the maximum equivalent tension is 896e6 Pa. Given that rupture resistance of the material is 460e6 Pa, it results that in that area the material is going to break.

- Wearing resistance

Wearing resistance may also be calculated:

![Figure 22. Wearing resistance.](image2)
SubJECTED to a symmetric alternating cycle, the bulk carrier’s structure shall break in the tension focus area after only 316 cycles or better said 6320 seconds, after which the crack extends inexorably.

4. Conclusions
Significant contributions brought by this paper and some of the most important conclusions are:
The modelled system through numerical analysis is a complex phenomenon. Simply said the sea waves move the bulk carrier in a particular way and then the bulkheads move water or fluid cargo (or dusty such as bauxite) and finely the sloshing phenomenon presses the structure of the ship often over her capacity. All these stages have been discussed in the paper’s chapters.
Not only fluids suffer from the sloshing phenomenon but also the dusty ones develop the same phenomenon which comes in line with what was shown by Lee et al., 2007a [84], who made a sensitivity study of the parameters of an LNG tanker using CFD (Calculator for Fluids Dynamics) with the conclusion that viscosity and density of the simulated fluids do not have a sensitive effect over the sloshing phenomena.
Density and pressure forces developed during the evolution of fluid in the cargo hold have an important effect over friction with the bulkheads and implicitly over shearing tensions which develop at the level of interfaces between fluid and bulkheads.
Moreover, it was shown that in the design process of the ship’s hull, it is essential to consider the sloshing phenomenon, a proper design having a serious impact on the extension of cracks in the structure with consequences on the life duration of the bulk carrier.

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