UDC 629.543:629.5.045.2:532.59

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An Overview of the Hydro-Structure Interactions During Sloshing Impacts in the Tanks of LNG Carriers

Review paper

An overview of the actual status of the modelling of hydro-structure interactions which occur during the severe sloshing impacts in the tanks of LNG Carriers of membrane type is presented. This problem still appears to be open and there are no fully satisfactory methodologies and methods available to solve this problem fully consistently within the so called direct calculation approach. That is why, for the time being, we still have to rely on simplified procedures. The paper first summarizes the main technical difficulties associated with this problem and then discusses the different methods which are employed in practice.

Keywords: *aeration, air pockets, hydroelasticity, hydro-structure interactions, impacts, model tests, sloshing*

Pregled hidrostrukturnog međudjelovanja prigodom udara zbog zapljuskivanja u tankovima LNG brodova

Pregledni rad

Članak prikazuje pregled trenutačnoga stanja u modeliranju hidrostrukturne interakcije koja se pojavljuje prigodom jakih udaraca od zapljuskivanja u tankovima plovila za prijevoz i skladištenje tekućega plina. Samo su tankovi membranskoga tipa uključeni. Ovaj problem još uvijek je otvoren i ne postoji potpuno zadovoljavajuće rješenje unutar takozvanog izravnog proračuna. Zbog toga se u praksi još uvijek upotrebljavaju pojednostavljene metode. Članak najprije daje kratak pregled najvažnijih tehničkih teškoća, nakon čega prikazuje različite metode koje se upotrebljavaju u praksi.

Ključne riječi: *aeracija, hidrodinamički udarci, hidroelastičnost, hidrostrukturne interakcije, modelska ispitivanja, zapljuskivanje, zračni džepovi*

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Received (Primljeno): 2012-10-17
Accepted (Prihvaćeno): 2012-10-22
Open for discusson (Otvoreno za raspravu): 2014-03-31

1 Introduction

This paper is devoted to the evaluation of the dynamic structural response of the cargo containment system (CCS) inside the membrane type LNG tanks of different floating units (ships, FPSO's …). Sloshing became a very important practical problem in the last decades due to the increased activities in the LNG transport. Large numbers of LNG Carriers were built or are under construction with the capacities which almost doubled as compared to the classical LNG Ships (from 138 000 m^3 to 240 000 m^3). The most common LNG ships belong to the so called membrane type. Within the membrane type concept, which is of main concern here, the LNG is kept liquid at very low temperature (-165 °C) by complex insulation system which is attached to the ship structure. At the same time as the size of LNG vessels increased, the operational requirements became more and more severe. Indeed, in the past, LNG ships were allowed to operate either in full or empty tank conditions, while today there is a necessity to allow for sailing at any partial filling. This requirement introduces serious difficulties in the design of both the containment system (CS) and the associated ship structure. Violent sloshing motions may occur (Figure 1) and the direct consequence is the occurrence of different impact situations which can induce the extreme structural loadings which can be devastating for both the containment system and the ship structure. As far as the hull structure is concerned the situation is slightly simpler and normally only global loads matter. Concerning the cargo containment system the situation is significantly more complex because CCS is directly exposed to the violent sloshing impact loading. Today two main types of CCS exist and they are shown in Figure 2. Both systems are owned by *Gaztransport and Technigaz* (*GTT*), and both systems are structurally very complex and involve different types of materials (plywood, perlite, invar, stainless steel, foam, glue…) which are connected together and attached to the hull structure.

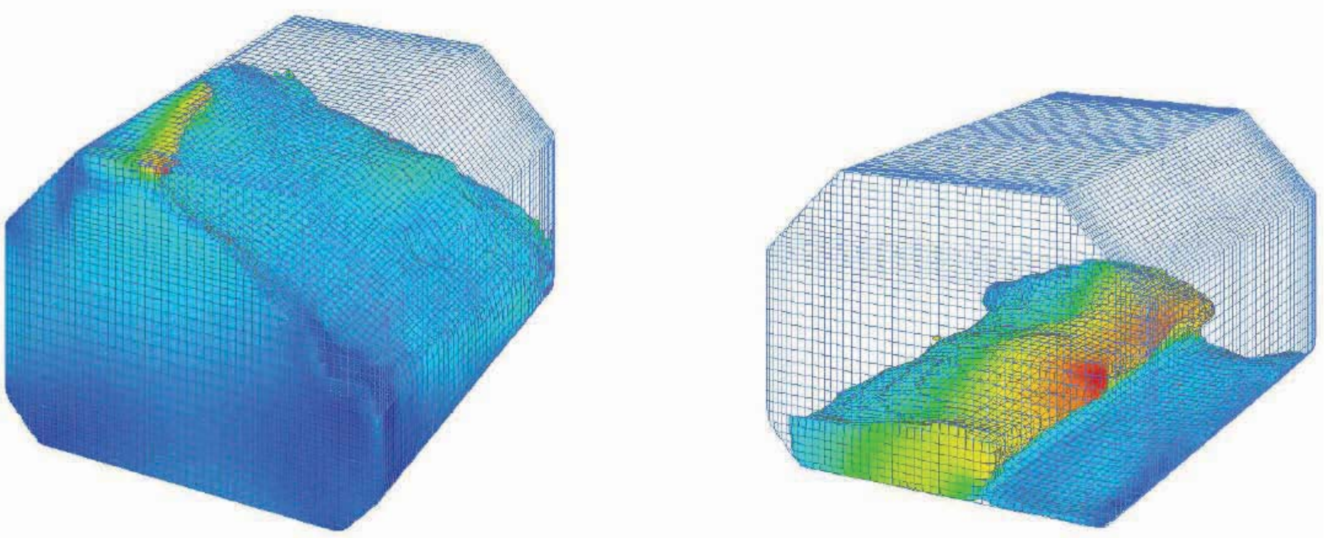


Figure 1 **Violent sloshing motions**
Slika 1 **Silovita gibanja pri zapljuskivanju**

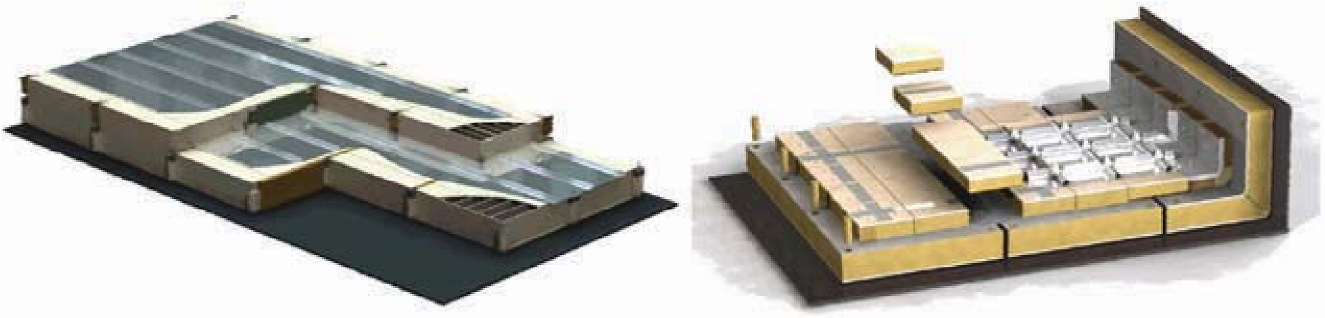


Figure 2 **Two types of containment systems NO96 (left) and MarkIII (right)**
Slika 2 **Dva oblika sustava obuzdavanja NO96 (lijevo) i MarkIII (desno)**

Because there are no numerical methods that can fully describe the sloshing induced slamming pressures, one has still to rely on experiments, which means in practice model tests. The challenges are how to scale the model test results to full scale and properly account for the structural elastic reactions due to the fact that a rigid model is used in model scale. There are many contributing factors to scaling which have to be considered and one has to do certain approximations. Generally speaking, Froude scaling is expected to be a dominant effect. Correct ratio between the density of the gas and the liquid, the Euler number due to possible gas pocket effects, boiling (cavitation number) as well as hydroelastic effects have to be considered. An implication is that the effects of viscosity (Reynolds number), surface tension (Bond number) as well as the change of the speed of sound due to a mixture of gas and liquid are likely to be of secondary importance. (Faltinsen et al. (2009) [1]).

The complex scaling issues are discussed, among others, by Yung et al. (2009) [2], where attempt was made to propose a rational scaling procedure. The authors conclude that, despite the thermodynamic complexities along the NG/LNG phase boundary, dynamic similitude for sloshing is possible for geometrically similar models regardless of length scale, provided that the Euler number, the Froude number and the Interaction index are the same. In particular, the Interaction index, which relates dynamic pressure communication between the ambient vapour and the sloshing liquid, provides a means to scale impact pressures for model tests with fluids available at convenient thermal conditions. The work of Yung et al. (2009) [2] was a part of very extensive research done by *Exxon Mobil* in cooperation with *GTT* (Kuo et al. (2009) [3], He et al. (2009) [4], Issa et al. (2009) [5]) with the final goal to produce a rational design methodology based on direct calculation approach. However, this very interesting methodology has not been applied in practice yet, which suggests that still many uncertainties exist.

Methodologies proposed by the Classification Societies for the practical design verification of the containment system are still essentially based on the so called comparative approach which relies on the use of the small scale model tests for reference and target ships. Within this comparative approach the small scale model tests on the reference ship, which does not experience any damage, are used to deduce the conservative pressure scaling factor and the same scaling factor is applied to the target ship. After that the resulting pressure loading at full scale is deduced and compared to the capacity of the containment system. The critical point in the analysis is obviously the scaling factor which does not have clear rational justification since it reduces hydrodynamic phenomena into a single number.

Let us also mention that the direct calculation methodology for sloshing requires, in addition to the evaluation of hydro-structure interactions during impacts, a complex seakeeping analysis which has to be fully coupled with sloshing dynamics. This is obviously necessary in order to determine the representative design tank motions. Finally, a very complex statistical analysis is required both on seakeeping and sloshing impact sides in order to simulate the ship life time.

2 Model tests

Many different types of model tests at different scales and with different objectives were proposed and performed in the last few years. In particular, small scale sloshing model tests have become nowadays rather standard and many important facilities exist all around the world, which allows for testing the tank models at scale up to 1/25. The most typical sloshing model testing facilities are based on the use of hexapod (Figure 3) which proved to be very efficient in generating arbitrary time history of tank motions.

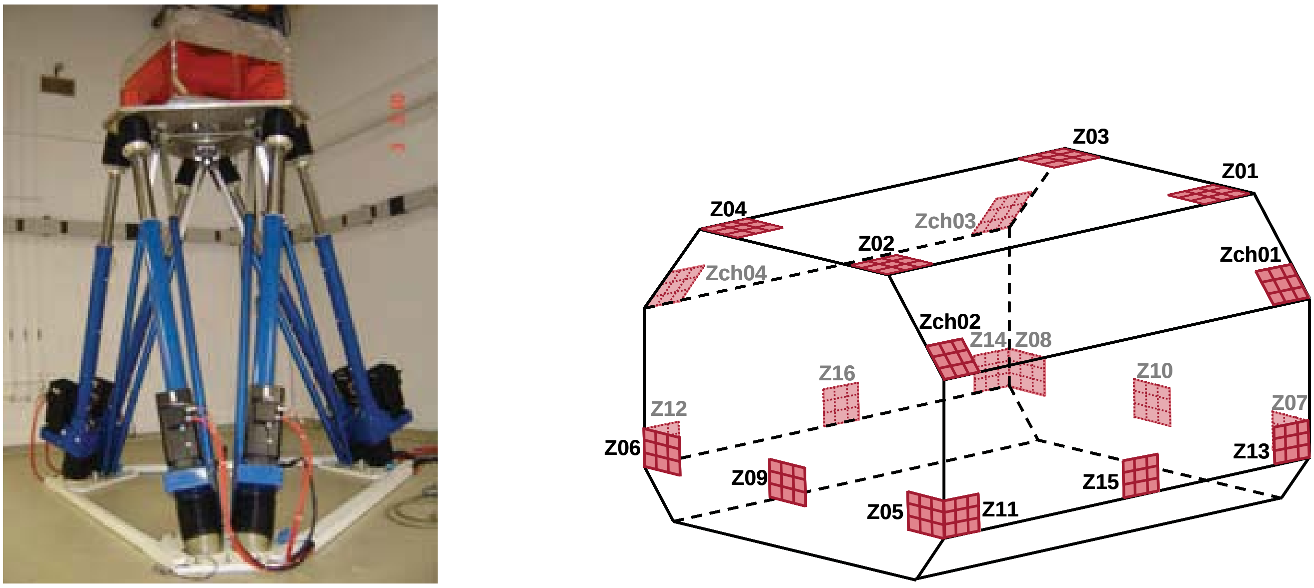


Figure 3 **Hexapod system for sloshing model tests and typical pressure sensor locations**
Slika 3 **Hexapodni sustav za modelska ispitivanja zapljuskivanja i tipični položaji senzora za mjerenje tlaka**

As far as the overall sloshing behaviour is concerned, the small scale model tests are very useful and give good qualitative impression of the violent fluid flow. At the same time the overall forces on the tank show good repeatability regardless of the model scale (Diebold et al. (2011) [6]). This is because the overall sloshing behaviour is mainly driven by the Froude scaling. When it comes to the measurements of pressure the situation is much more complicated both regarding the repeatability and accuracy of the pressure measurements and, as already indicated, regarding the scaling of the measured pressure to the full scale. Different work on small scale model tests were published in the last few years (Kim et al. (2009) [7], Maillard et al. (2009) [8], Repalle et al. (2010) [9]).

In Abrahamsen et al. (2011) [10], a dedicated model tests to investigate the specific impact type on the roof of the rectangular tank were performed (Figure 4). The impact type is the one with the entrapped air pocket. The goal was to investigate the decay of the oscillations in the air pocket and possible sources of damping. Authors concluded that the leakage is not the main cause of decay and that heat transfer in between air and water might be important. Similar investigations were done by Lugni et al. (2010) [11,12] where the breaking wave impact involving the air pocket entrapment was studied under different ullage pressures. One of the conclusions is that the influence of the ratio between ullage and vapour pressure plays an important role and the decay of oscillations is much stronger in the vapour pressure regime. This suggests that the phase transition in between liquid and vapour phases plays an important role for damping the pressure oscillations.

This fact was also confirmed by Braeunig at al. (2010) [13] where this phenomenon was investigated both experimentally (water and steam) and numerically. In Figure 5 the difference in between the pressure signals with and without phase transition is obvious. All this illustrates again the difficulties related to the scaling of the model test results.

Very extensive experimental database of drop tests at small or full scale were produced at *Pusan National University* by the team of Prof. Kwon (Chung et al. (2007) [14], Kim et al. (2008) [15], Oh et al. (2009) [16], Kwak et al. (2010) [17], Oh et al. (2010) [18]). Very useful pressure measurements and high speed video of different impact types on NO96 and MarkIII geometries were produced. These types of measurements are essential for

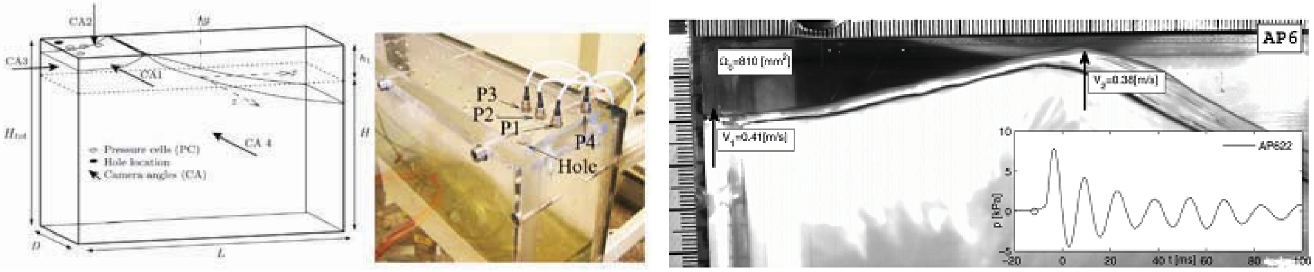
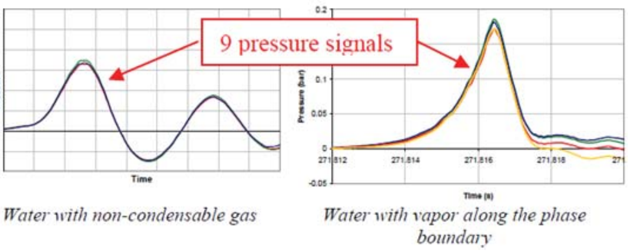


Figure 4 **Model tests on impact involving the air pocket and typical pressure signal**
Slika 4 **Modelska ispitivanja na udarce koja uključuju zračni džep i tipičan signal tlaka**



Water with non-condensable gas *Water with vapor along the phase boundary*

Figure 5 **Air pocket pressure signature for different conditions**
Slika 5 **Zapis tlaka u zračnom džepu za razne uvjete**

better orientation of the numerical developments and for their subsequent validation.

Driven by the difficulties related to the scaling, a very ambitious experimental project Sloshel (Brosset et al. (2009) [19]) was initiated by *GTT*, *Bureau Veritas*, *MARIN* and *Shell*, and has been joined later by *American Bureau of Shipping*, *Ecole Centrale Marseille*, *Chevron*, *ClassNK*, *Det Norske Veritas* and *Lloyd's Register*.

The originality of the experiments performed within Sloshel project lies in the fact that the real CCS was impacted by realistic wave impact conditions at full scale, Figure 6. The only, non negligible however, drawback is that water under atmospheric conditions was used instead of LNG. Very extensive database of both loading (pressures, forces…) and the structural response of the CCS was collected both for NO96 and MarkIII CCS. Maximum measured pressures went up to 56 bars but still no significant damage of the CCS was observed. Thanks to the Sloshel experiments significant progress in understanding of the physics of the sloshing impacts was made.

The fundamental importance of the local flow characteristics before the impact was confirmed. This means that every detail counts, which makes the direct assessment procedures very complex. This also means that the analysis of the small scale model tests, where the corrugations (MarkIII) or raised edges (NO96) are not present, should be done with the greatest care. Among other interesting results from the Sloshel full scale experiments, it is worthwhile to mention the detailed analysis of the fluid flow evolution during the different impact situations. One example of typical impact on MarkIII CCS is shown in Figure 7.

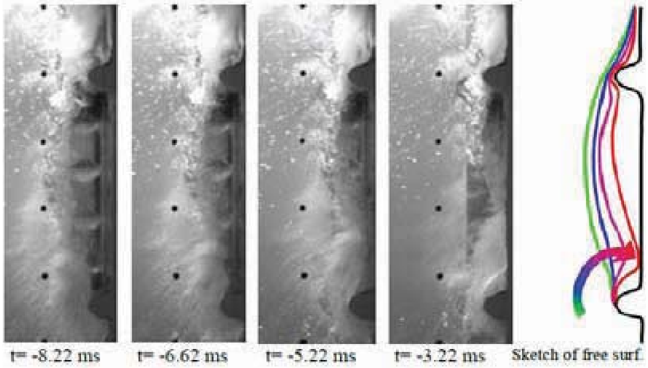


Figure 7 **Different phases of the fluid flow during the impact on MarkIII CCS**
Slika 7 **Razne faze protoka tekućine za vrijeme udara na Mark III CCS**

Following these investigations, Brosset et al. (2011) [20] proposed the classification of the different impact phases into different elementary loading processes (ELP). In that respect three

Figure 6 **Quasi full scale impact experiments (Sloshel project)**
Slika 6 **Mjerenja kvazi naravnih udara (projekt Sloshel)**

main ELP's were identified: (1) the actual impact (discontinuity of velocity), very localized and inducing acoustic pressure with the local velocity of sound of the aerated water; (2) the building of a jet along the wall from the impact area; (3) the compression of entrapped gas pockets or escaping gas jets. The idea behind this classification seems to be the decomposition of the arbitrary impact situations into different ELP's. Once each ELP properly assessed (still not clear how!), the final result will be the sum of the different ELP's in time. This work is still in progress and no final conclusions have been made yet. Many other interesting issues (scaling - Bogaert et al. (2010) [21], deformation of the foam - Kaminski et al. (2011) [22]…) were investigated within the Sloshel project and the analysis of the huge databases is still in progress.

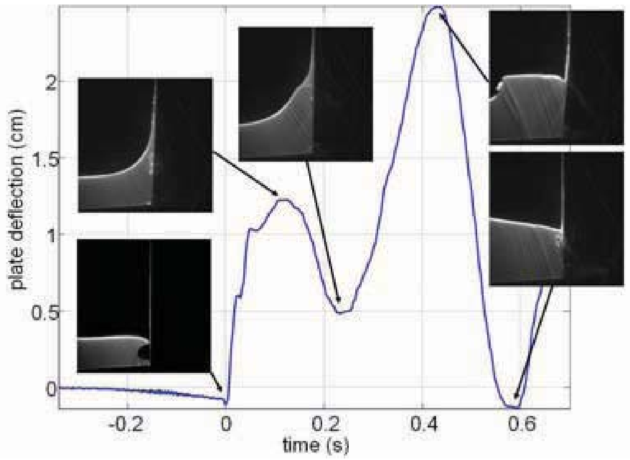
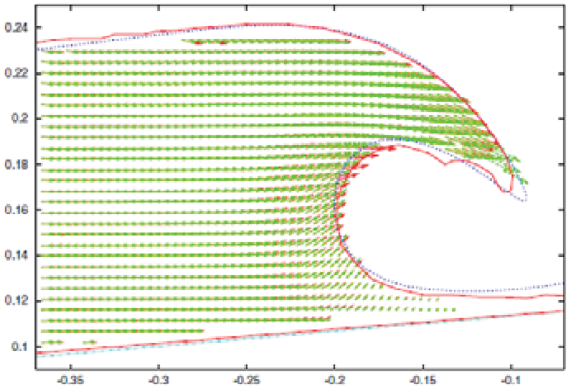


Figure 8 **Large scale impact experiments (MiniSlo project)**
Slika 8 **Mjerenja udara u velikom mjerilu (projekt MiniSlo)**

At the same time, Sloshel project generated very important research activities which accompanied the full scale tests. Indeed, during the full scale experiments different difficulties were identified, one of the main being the lack of repeatability of the measurements for some important impact conditions. It was thus decided to investigate this issue on a smaller scale and on a more simplified elastic structure. The MiniSlo project was organized and medium scale model tests were performed in *Ecole Centrale de Marseille* [23,24]. Measurements of the fluid flow (PIV) pressures and structural deflections were undertaken and very useful database for validation of the numerical codes was produced. Due to the well controlled laboratory conditions, the repeatability of the measurements was very good. One example of the measurements is shown in Figure 8. It is very likely that this kind of experiments will have larger importance in the future.

Parallel to the experimental work, important numerical activities were also performed within the Sloshel project (Oger et al. (2009) [25], Wang et al. (2009) [26], Braeunig et al. (2009) [27], Maguire et al. (2009) [28], Pillon et al. (2009) [29], Malenica et al. (2009) [30], Guilcher et al. (2010) [31], Dobashi et al. (2010) [32], Carden et al. (2011) [33,34], Wang et al. (2011) [35], Lee et al. (2011) [36], De Lauzon et al. (2011) [37]). Different types of numerical methods were used (volume of fluids CFD, smooth particle hydrodynamics (SPH), semi analytical methods …) for both rigid and hydroelastic types of hydro-structure interactions. In spite of all the efforts there still seems to be no fully efficient numerical method able to simulate this problem consistently.

Different other works on small/medium scale model tests were done in the last few years (Kim et al. (2009) [7], Maillard et al. (2009) [8], Repalle et al. (2010) [9], Kim et al. (2011) [38], where different phenomena were investigated (pressure statistics, impact flow evolution, influence of density ratio…). One very important aspect of the model tests is the statistical property of the pressure measurements. A large degree of uncertainties and scatter is usually observed (e.g. Fillon et al. (2011) [39]). In this context, it is also important to mention that each pressure signal is not characterized by its maximum value only but the pressure should always be analyzed in combination with its time history (rise and decay time, oscillations…) and the surface which is affected. This introduces additional non-trivial technical difficulties into this already complex problem.



3 Numerical simulations of sloshing

Different numerical methods for sloshing are proposed in the literature (e.g. Godderidge et al. (2009) [40], Chen et al. (2009) [41], Wemmenhove et al. (2009) [42], Rudman et al. (2009) [43], Ma et al. (2009) [44]…). These methods are mainly based on either potential flow, Euler or full Navier-Stokes assumptions. Different numerical approaches which are usually employed are: BEM-Boundary Element Method, CIP-Constrained Interpolation Profile method, FDM-Finite Difference Method, FEM- Finite Element Method, FVM- Finite Volume Method, LS-Level-Set method, MAC-Marker-and-Cell method, MPS-Moving Particle Semi-implicit method, SPH-Smoothed Particle Hydrodynamics method, VOF=Volume-of-Fluid method and others. Typical results of CFD simulations, in terms of global liquid behaviour, are presented in Figure 1.

Within the numerical methods for modelling of sloshing it is also worthwhile to mention the nonlinear analytically-based multimodal method proposed by Faltinsen et al. (2009) [1,45]. The advantage of the method is its semi-analytical character which allows for fast calculations and detailed separation of different driving phenomena in sloshing. However, even if this method gives good insight into the overall sloshing motions, it cannot be directly applied to the analysis of sloshing impacts.

With respect to all the numerical work which has been done, it is fair to say that there is still no fully efficient numerical method to deal with the overall sloshing hydro-structure interactions in a consistent way. Indeed it appears that, from computational point of view, it is impossible to account for all the different physical effects at the same time. This is not only because of the prohibitive CPU time requirements but also because of the complexity of the physical phenomena which are involved (violent free surface deformations, hydroelasticity, phase transition, compressibility, 3D effects, low temperature …). That is why the actual research is more oriented to a kind of hybrid approach where the problem is subdivided into global and local parts. Indeed, the global fluid flow during sloshing can be reasonably described by the classical CFD tools but the complete treatment of the complex impact situations at the same time, appears to be impossible today. With respect to this, CFD can be used to determine the local conditions before impact (essentially the relative geometry and the relative impact velocity distribution) and the dedicated models for local impact simulations can be used for evaluation of the CCS structural response. This idea was first introduced by Korobkin et al. (2006) [46] and the most recent advances were presented in Ten et al. (2011) [47]. For different impact types (steep wave impact, impact with air-pocket, aerated impact and their combinations), which were identified for the low filling levels, the semi-analytical (or semi-numerical) approach for fluid–structure interactions has been presented. Within this approach, the fluid flow is treated using the semi-analytical methods while the structural part is solved using the three-dimensional finite-element model. The choice of the simplified semi-analytical approach for the fluid flow was made in order to be able to have a full control of the flow characteristics, which allows for detailed investigations of the influence of different physical parameters. One example of the typical simplified impact situation is shown in Figure 9.

Different papers on the specific impact types were presented by the team of Prof. Korobkin (Khabakhpasheva et al. (2009) [48,49], Malenica et al. (2009) [30], Ten et al. (2009) [50,51], Khabakhpasheva (2011) [52]). This work is ongoing and there is still a lot of work to be done especially concerning the validation of different impact models. In that respect it is important to mention one of the recent papers [57] done in the team of Prof. Korobkin which treats the complex problem of impacts on the corrugated panels under the conditions similar to those from Figure 7. The practical idea behind this global-local approach is to perform simplified parametric calculations for different impact configurations involving a small number of impact parameters (impact velocity, aeration, air-pocket volume, relative angle in between fluid and structure…) and check the structural resistance. Parallel to that the CFD (or alternatively small scale model tests) will give the most probable maximum value of the impact parameters. Both global and local results will then be combined

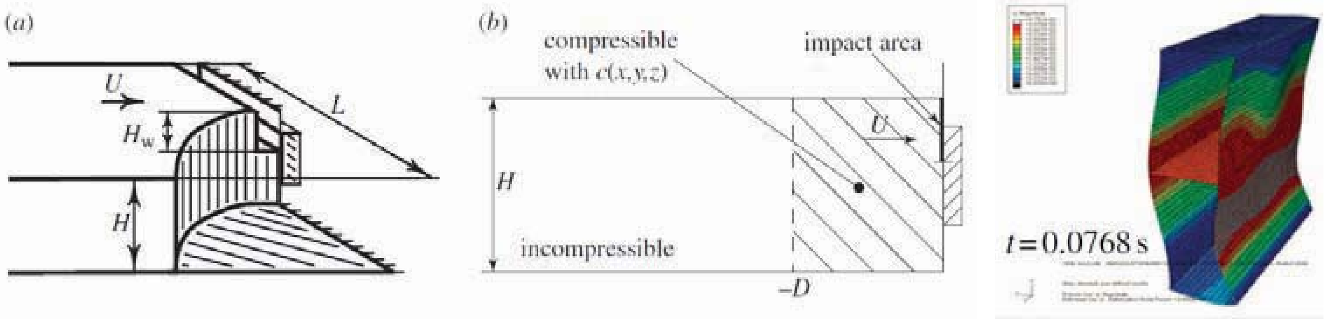
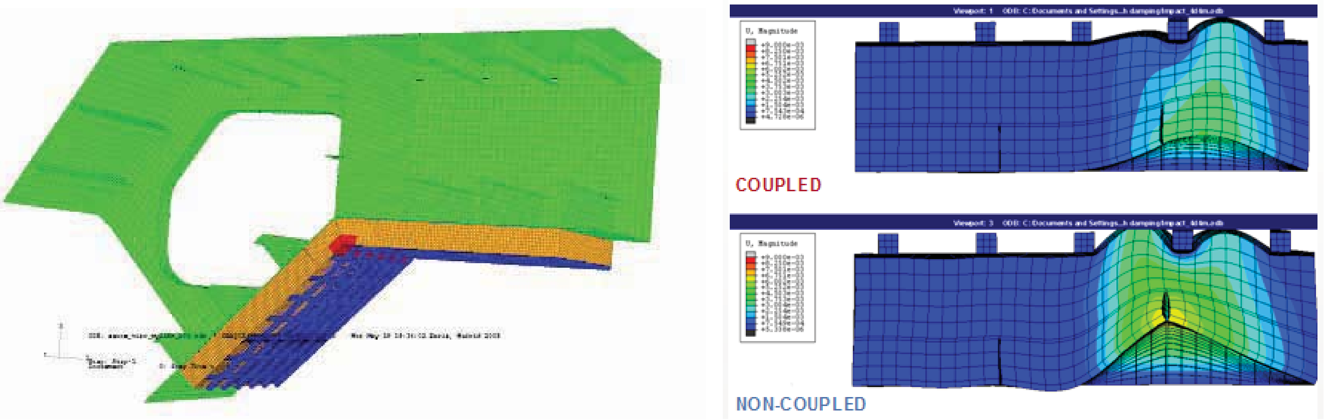


Figure 9 **Example of simplified semi-analytical model for partially aerated impact type**
Slika 9 **Primjer pojednostavljenog polu-analitičkog modela za djelomično zračan tip udara**

Figure 10 **3DFEM structural model and comparison of the quasi static (non-coupled) and hydroelastic (coupled) structural responses**
Slika 10 **3DFEM strukturni model i usporedba kvazistatičkih (nespregnutih) i hidroelastičnih (spregnutih) odziva strukture**



in order to make the final check of the structural integrity of CCS. Similar ideas based on the exclusive use of CFD for both global and local flow was presented by Cho et al (2008) [53].

Another example of calculations using this approach, which demonstrates the importance of hydroelasticity, is shown in Figure 10.

Finally, let us also mention one important problem, which does not seem to have received enough attention in the literature, and which concerns the numerical modelling of the CCS structure. As already indicated, CCS is a very complex structure composed of different materials connected together by special procedures and the representativity of the classical finite element models should be considered more seriously. Even if some work on this issue has already been done (Issa et al. (2009) [5], Arswendy et al. (2011) [54,55]) this point requires more careful attention.

4 Conclusions

Sloshing induced impacts are important in the design of a ship tank. Many physical effects may have to be considered such as gas cushion, liquid compressibility, boiling of liquid cargoes and hydroelasticity. When analyzing sloshing impacts, one must always have the structural response in mind. An important consideration is the time scale of a particular hydrodynamic effect relative to wet natural periods for structural modes contributing significantly to large structural stresses. More structural modes may be needed for membrane structures analyses than for steel structures. Some of the important structural modes for membrane structures may have relatively lower natural periods than for steel structures. If the time scale of a hydrodynamic effect, as for instance acoustic effects, is very small relative to important structural natural periods, the structure has a negligible reaction and therefore the particular hydrodynamic/hydroelastic effect can be neglected. When the hydrodynamic loads occur on the time scale of important structural modes, hydroelasticity must be considered. This implies that the fluid (liquid, gas) flow must be solved simultaneously with the dynamic elastic structural reaction.

It is common in tank design to do model experiments for sloshing-induced impact effects by means of forced oscillation tests. However, the scaling of the model-test results represents a challenge due to the many physical effects that may matter. Usually, the Froude scaling is applied for small scale model tests. This formulation yields conservative values for maximum pressure. However, it is important to note that the time is also differently scaled by different scaling laws. The relationship between temporal characteristics of the load and the structural response is nonlinear and dependent on these characteristics related to the natural period of the structure. Therefore, the effect of scaling the pressure time histories may only be assessed by analyzing the dynamic response of the containment system.

The quasi full scale model tests and intermediate scale model tests are believed to be very useful bringing more light into this difficult problem even if the preliminary conclusions from these tests are not fully conclusive.

On numerical side, it appears that the correct numerical modelling of hydro-structure interactions during the sloshing impacts inside the LNG tanks is still beyond the state of the art and there is still no rational direct calculation procedure to be used for design verification of the CCS.

The full scale measurements and monitoring of the real LNG ships would be extremely helpful for better understanding of the way how the CCS is “suffering” in reality. Indeed, with respect to all the difficulties discussed above, it appears clearly that more feedback from experience is necessary in order to get more confidence into the existing design procedures. How to perform these full scale measurements is another complex question.

In any case, the actual situation is that, for the design verification of CCS, we still rely on the so called comparative approach. Finally, it is very important to mention that, in spite of all the imperfections of the comparative approach, the overall safety record of LNG floating units is excellent and only few incidents were experienced (Gavory et al. (2009) [56]).

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MEST) through GCRC-SOP.

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