HYDROELASTIC IMPACTS IN THE TANKS OF LNG CARRIERS

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ABSTRACT

The paper deals with the methods for evaluation of the hydro-elastic interactions which appear during the violent sloshing motions inside the LNG tanks. The complexity of both fluid flow and the structural behavior (containment system + ship structure) do not allow for fully consistent direct approach according to the present state of the art. Several simplifications are thus necessary in order to isolate the most dominant aspects and treat them properly. Here, we discuss the recent developments conducted in the Research Department of Bureau Veritas in cooperation with Lavrentyev Institute of Hydrodynamics and Ecole Generaliste des Ingenieurs de Marseille. These developments are mainly based on the asymptotic approaches for fluid flow (Wagner, Bagnold, Korobkin, ...), which are coupled with the commercial finite element codes for the structural response.

KEYWORDS

Sloshing; impact; hydro-elasticity; Wagner approach; entrapped air; aerated impact; incompressible model; compressible model.

1. INTRODUCTION

LNG transport by ships is receiving more and more attention nowadays. The most common LNG carriers belong to the, so called, membrane type and an typical example is shown in Figure 1. At the same time, the operational requirements for LNG vessels are getting 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 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 (e.g. see Figure 2) and the direct consequence is the occurrence of different impact situations which can induce the extreme loadings on the tank structure.

The correct numerical modelling of the fluid-structure interactions during the sloshing impacts is extremely complex, and it is fair to say that, up to now, there is no satisfactory numerical model
able to treat these situations in a fully consistent manner. Even without considering the interaction with the structure (hydroelasticity) the modelling of the pure fluid flow makes serious problems due to several complex physical phenomena involved (rapid change of geometry, two (three) phase flow in some situations, low temperature of the LNG (-165°C), important 3D effects, prohibitive requirements for the mesh size and time steps, ...). In addition to these pure fluid mechanics problems, and due to the flexibility of the CS, another important aspect which seems to be essential for correct evaluation of the structural responses is the effect of hydroelasticity. Indeed, due to the violence of the impacts, the hydrodynamic pressure will depend on the structural response so that fully coupled hydro-structure model is necessary. In order to better understand the modelling difficulties related to hydroelasticity, in Figure 1 we show two typical containment systems which are in use today. The first one is the so called NO96 system, which is composed of plywood boxes filled with perlite, while the second system, called MARK III, is composed of the different levels of foam combined with plywood structure. On the side in contact with LNG, both systems have the membrane made of special metal alloy called invar. In the case of NO96 CS, this membrane is flat, while it is corrugated for MARK III CS.

In this paper, general methodology for evaluation of the structural responses caused by the violent sloshing impacts, is proposed. This methodology is based on the composite approach which “mixes” the general CFD fluid mechanics codes, small scale model tests, general FEM structural codes and asymptotic theories of liquid impact.
2. OVERALL METHODOLOGY

The basic idea of the present approach is to "take" the good parts of all the available tools and combine them into well controlled procedure able to take into account the most important physical aspects in order to identify the most dangerous conditions from structural resistance point of view. The overall sloshing flow in prescribed ship loading conditions is evaluated by combining the seakeeping tool with 3D CFD code and/or small scale model tests. These simulations are performed without accounting for the flexibility of the containment system and the ship structure, and this part of the analysis is used to identify the most dangerous places and impact configurations induced by the violent sloshing motions. Note that, due to large dimensions of the LNG tanks, the CFD calculations can be performed only with relatively large cells, and that is why neither impact pressures nor the elastic responses of the tank walls can be simulated in a reliable way. On the other hand, if the small scale model tests are used, instead of CFD, the measurements of the violent impact pressures are not very reliable and their transfer to a full scale is uncertain. In summary, it appears that the efforts made for calculating or measuring pressures are subject to extreme difficulties, so that the methods of the structural assessment based exclusively on the measured or calculated pressure values, are not recommendable. On the other hand, we should keep in mind that the end results of the analysis is not the pressure but its effects i.e. structural responses. Indeed, even if the measured, or calculated pressure, can be extremely high, they are not necessarily dangerous for the structure, because the structural response depend not only on the maximum pressure values but also on its spatial and temporal distribution in combination with the structural characteristics (natural periods, damping, ...).

All this, indicates the necessity for dedicated hydro-elastic models for different impact types. Once the impact conditions have been properly identified, local hydroelastic analysis based on using the asymptotic fluid flow models combined with the commercial FEM tools is used. The local hydroelastic analysis is applicable only during the impact stages, when the hydrodynamic loads are high and the elastic response of the insulation system is maximal. By definition the impact stage is of short duration. This makes it possible to disregard many effects, which are of main concern in the CFD analysis, such as large dimensions of the tank and its real shape, real profile of the free surface at a distance from the impact region, viscosity of the fluid, its surface tension and gravity effects. However, some effects, which are believed to be of minor importance in the CFD analysis, should be taken into account in the local analysis. These effects are compressibility of the fluid, presence of the gas above the fluid surface and in the impact region, aeration of the fluid in the impact region, jetting and fine details of the flow in the jet root region, rapid increase of the wetted surface of the tank wall and the flexibility of the wall. Short duration of the impact stage allows us to simplify the local analysis and to use a combination of analytical and numerical methods instead of direct numerical calculations. Analytical part of the local analysis is very important because it allows us to:

(i) obtain useful formulae suitable for design needs,

(ii) control numerical results,

(iii) treat properly the coupled problem of fluid-structure interaction during the impact,

(iv) determine the wetted part of the wall at the same time with the fluid flow and the pressure distribution.

The last point is crucial in the context of Wagner type of the impact, when the rate of the wetted area increase is higher that the accelerations of the liquid particles and standard schemes of integration in time used in CFD become inappropriate.
In this paper, it is suggested to use simplified hydrodynamic models in combination with complex structural models during the impact stage. This idea is based on the experience gained already in both theory and applications that semi-analytical models of violent flows during impact stage are comparable with fully nonlinear calculations performed with high resolution in space and in time. In many cases the impact conditions and aeration of the fluid in the impact region are not well defined and small change of global conditions may lead to significant changes of the local impact conditions. This is why, in some sense, attempts to reproduce all details of the flow, shape of the flow region and the fluid characteristics have no meaning in practice, even if they lead to very interesting mathematical problems.

We distinguish three main types of the impact:

(i) Steep wave impact [15]
(ii) Breaking wave impact [1, 4]
(iii) Aerated fluid impact [13]

Generic examples of these impacts are schematically presented in Figure 3. Different variants may also exist. In this paper, the general methodology is shown only for the case of steep wave impact and other two impact types are just briefly mentioned. More details about them can be found in [1, 4, 14, 15].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Different impact types, (a - steep wave impact, b - breaking wave impact, c - aerated fluid impact).}
\end{figure}

\section{3. STEEP WAVE IMPACT}

This type of the impact occurs when the wetted area of the structure increases at a high rate and presence of the gas outside the fluid can be safely neglected [15]. Close to the impact region the fluid can be in contact already with the structure, as it is happening in the case of steep wave impact in low filling situations, or not, as in the problem of liquid impact on ceiling.

Depending on the flow region shape and the flow field before the impact the fluid is treated as incompressible or compressible. The fluid should be considered as compressible if the wetted area
increases at very high rate, which is comparable with the sound speed in the fluid [9]. If the rate of the impact region expansion is high but much less than the sound speed, the incompressible fluid model should be used. In this case the corresponding impact type is referred to sometimes as the Wagner type [17].

3.1 Acoustic approximation

As mentioned above, in the case of the almost flat impact on the wall, the situation is simplified in a manner shown in Figure 4, where the corresponding boundary value problem for the unknown potential $\varphi$ is also shown. As we can see the fluid is assumed to be compressible. The method which is used to solve this problem, for rigid wall, can be found in [5].

$$\varphi = 0$$
$$c_s^2 \Delta \varphi = \varphi_{tt}$$
$$\varphi_y = 0$$
$$\varphi_x = -U$$
$$\varphi_x = 0$$

Figure 4: Hydraulic jump and corresponding boundary value problem.

3.2 Wagner approximation

In the case where the wave front of the fluid hits the wall with an angle, the problem can be classified as a Wagner type [17]. Typical situation is shown in Figure 5. For this model the fluid is assumed incompressible. The main difficulty is related to the evaluation of the wetted part $b(t)$ of the wall at each time instant. Indeed the rate of expansion of the wetted part is probably the most important parameter in the Wagner type of impact because the pressure time history, its spatial distribution and maximum pressure value, directly depends on it. Important experience exists in solving this type of problem both for rigid and elastic impacts [7].

$$\phi = 0$$
$$\Delta \phi = 0$$
$$b(t)$$
$$\phi_y = 0$$
$$\phi_x = -U$$
$$\phi_x = 0$$

Figure 5: Wagner type impact and corresponding boundary value problem.
3.3 Hydroelasticity

In the case of impact onto elastic structure, the boundary condition at the interface will change, in order to take into account the structural deformations and their influence on fluid flow. In the case of acoustic approximation [6], the boundary condition on the wall change to:

\[
\varphi_x = w_t(y, t) \quad (x = 0, \ 0 < y < H_w),
\]

\[
\varphi_x = -U + w_t(y, t) \quad (x = 0, \ H_w < y < H_w),
\]

where \( w_t(y, t) \) is the velocity of deformation of the wall.

In the case of Wagner approach the wall conditions become:

\[
\phi_x = w_t(y, t) \quad (x = 0, \ 0 < y < H_w),
\]

\[
\phi_x = -U + w_t(y, t) \quad (x = 0, \ H_w < y < b(t)),
\]

\[
\phi = 0 \quad (x = 0, \ b(t) < y < H),
\]

(2)

In order to be able to build up the fully coupled hydroelastic solution, we need to introduce the additional potential related to the velocity of the structural deformations. Several possibilities exists to solve the fully coupled hydroelastic problem [8]. Most common ones are based on either normal mode decomposition method [10] or on finite element method [11]. The main difference lies in the representation of the structural displacements which are decomposed into the series of dry eigenmodes in the normal mode method, while the classical finite element representation is used in the finite element method. The main advantage of the normal mode method lies in the possibility of having the extremely simple semi-analytical solutions for some basic structural situations. The finite element method is more general and in principle can handle any kind of structures, but it requires rather sophisticated structural software and more important changes inside the structural codes are necessary.

It is important to note that an intermediate solution is also possible. It consists in using the general FEM software for calculation of the structural natural modes while the hydrodynamic and hydro-elastic coupling parts are done in a way similar to that used in the normal mode method. The advantage of this approach lies in the rather clear separation between the structural and hydrodynamic parts so that the method can be adapted to any general FEM code without major difficulties.

Regardless of the method which is chosen for representation of the structural deflections, the formal procedure remains similar and we end up with the following types of coupled hydroelastic equations:

**Acoustic model:**

\[
\frac{\partial^2}{\partial t^2} \left\{ \mathbb{M} \mathbf{W} + \int_0^t \mathbb{S}(t-\tau) \mathbf{W}(\tau) d\tau \right\} + \mathbb{K} \mathbf{W} = \mathbf{Q}_r(t).
\]

(3)

**Wagner model:**

\[
\frac{\partial^2}{\partial t^2} \left\{ [\mathbb{M} + \mathbb{S}(b)] \mathbf{W} \right\} + \mathbb{K} \mathbf{W} = \mathbf{Q}_r(b),
\]

(4)

where \( \mathbf{W} \) denotes the unknown structural response, the ”dry” structural characteristics are represented by structural mass matrix \( \mathbb{M} \) and stiffness matrix \( \mathbb{K} \), and the hydrodynamic action is subdivided in two parts: the first one which is independent of the structural deformations \( \mathbf{Q}_r \) and the second one \( \mathbb{S} \) which depends on the structural deformations. The matrix \( \mathbb{S} \) represents the coupling effects and is essential for hydroelastic models. In the case of incompressible Wagner impact it can be assimilated to the added mass matrix, while in the case of acoustic approximations it represents the memory effects of the fluid flow due to the time history of the structural deformations. Note that, some other representations of the fully coupled hydroelastic model are also possible but these two are the most common ones.
3.4 Few numerical results

In order to briefly illustrate the basic effects of hydroelasticity, here below we present some results for Wagner type impact. The case of a steel beam clamped at two ends entering water with constant velocity of 10\text{m/s} is chosen. The beam length is 0.8\text{m}, the thickness is 20\text{mm} and two different deadrise angles (gamma) were considered (6 and 8 degrees). Note that three different methods were used (normal mode method [10], finite element method [11] and method based on variational inequalities [3]) and all of them gave the same results.

In Figure 6, first we present the pressure time history in the middle of the beam for both rigid and hydroelastic impact. We can clearly appreciate the important influence of the small changes in the impact conditions. Indeed, in the case of the rigid beam, only 2 degrees of difference in the deadrise angle results in almost doubling of the maximum pressure and in the significant change of the pressure time history. On the other hand, in this particular case, the hydroelastic effects significantly reduce the maximum pressure (Figure 6b). However, as shown in Figure 7a, the 2 degrees changes in the deadrise angle, has much less influence on the beam deflection and the deflection increase is approximately 15% only. Finally, in Figure 7b, the difference between the fully coupled and uncoupled approach (no added mass effects) is shown in order to stress, once again, the necessity for the fully coupled hydroelastic model. The effect of hydroelasticity should be expected to be much more pronounced for a beam of smaller thickness and especially for the containment system.

All this shows that the hydroelastic effects should be treated properly, and no correct conclusions can be made by considering only the information about the maximum ”rigid” pressures. The spatial and temporal pressure distribution together with the structural characteristics need to be taken into account consistently. Any eventual simplification of the problem should account for all these effects and that is not simple task.

![Figure 6](image_url)

Figure 6: Pressure time history for rigid (left) and elastic (right) beam and for 2 different deadrise angles.

Figure 8 presents more complex results for a realistic containment system (MARK III) attached to the ship structure. These results were obtained by coupling the asymptotic Wagner approach with commercial FEM code ABAQUS using the method described in [11]. Once again, we can see that the difference between the fully coupled and uncoupled approaches is important so that we can not disregard the effect of hydroelasticity. However, in some cases which are not represented here, the difference between the fully coupled and uncoupled approaches might be negligible so that uncoupled approach (much easier to put in practice) can be safely used. The problem is that it is very difficult to know in advance if the hydroelastic effects will be important or not because that depends on so many parameters and even small changes in the impact conditions, or in the structural properties, or in the boundary conditions, can lead to a completely different conclusions. The hydroelastic effects should...
depend on the relation between the intensity of the excitations (spatial and temporal distribution) and the structural natural periods. The difficulty is that the wet natural periods should be considered and they depend on the added mass of the liquid which also change in time.

All this means that, unfortunately, there is no simple method to take into account hydroelastic effects and fully coupled approach should be used.

3.5 Coupling with global sloshing motion

The theory presented above, considers rather simplified situations where the impact conditions (geometry and velocity) are constant and simply prescribed in advance. However, the real sloshing situations involve rather complicated fluid flow (see Figure 2) and impact conditions should be modified in order to account for the overall fluid flow. Under the assumptions adopted here, which are based on the asymptotic local analysis, it can be shown that accounting for the overall sloshing flow results in changing the boundary conditions at the wall only. This condition becomes dependent on the spatial distribution of the velocity and on the different relative geometry between the structure and the liquid. This means that from all details of the wave front approaching the vertical wall, we need only the shape of the wave front and its velocity before the impact stage. It is assumed that geometry of the upper part of the wave at some distance from the impact place is not very important for the interac-
tion process and can be approximated as flat. This approximation is supported by the fact that the solution of boundary value problem decays exponentially with the distance from the impact region. Let us also note that accounting for the global sloshing flow, imply the changes of the so called Wagner condition which is necessary for determination of the time history of the wetted part. However, this do not introduce the major difficulties and the original Wagner approach can be efficiently adapted.

3.6 3D effects

Another important aspect of the sloshing impact problem is related to the 3D effects which are obviously present in reality (Figure 2). Unfortunately, the fully consistent account for 3D effects represents the major difficulty and seems to be beyond the present state of the art. Indeed, even rigid body general Wagner type impact is still challenging problem and no efficient solution exists even if some significant progress was made recently [2, 8, 12, 16]. The exception are the 3D axisymmetric impact problems which can be solved in a similar way as 2D after performing the Fourier transform in the circumferential direction.

![Figure 9: NO96 containment system response to sloshing impact using 3D strip approach.](image)

However, some reasonably good approximations can be adopted, and below we briefly describe the so called 3D strip approach. The 3D strip approach is based on the coupling of the 2D stripwise hydrodynamic solutions with the full 3D structural models. This approach is likely to be conservative as compared to the full 3D approach because the 3D hydrodynamic effects usually tends to reduce the loading. One example of calculations performed using the 3D strip approach for NO96 containment system is shown in Figure 9.

4. CONCLUSION

We discussed here the problems related to the hydroelastic sloshing impacts which occur in the tanks of LNG carriers. The complexity involved in the interactions are enormous and no fully satisfactory method exists today. The main ideas of our approach are based on the assumption that the different impact situations can be classified into 3 main types (steep wave impact, impact with entrapped air and impact with aerated fluid) which are subsequently simplified and solved using the asymptotic
impact theories fully coupled with general structural finite element codes. In this way we can still keep the main physical parameters and control them efficiently in order to check the sensibility of the structural responses. The adopted procedure has been demonstrated on the Wagner type impact and other impact types are under consideration within the several research projects.

References


