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Fluid impact onto a corrugated panel with trapped gas cavity

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ABSTRACT

Initial stage of incompressible liquid impact onto a corrugated elastic panel with account for compressible gas trapping between the corrugations is studied. The liquid free surface is flat and parallel to the panel before impact. The impact velocity is constant in this study. The corrugations are modelled as identical rigid short structures on the surface of the flat panel. The panel is either of infinite or finite length. There are only two corrugations which are placed symmetrically on the panel. Only a part of the panel between these two corrugations is elastic. The liquid free surface closes the gas cavity between the two corrugations at the initial instant of impact and compresses the gas before the fluid comes in contact with the elastic part of the panel. The elastic deflections of the panel are caused by gas pressure in the cavity. The elastic deflections modify both the pressure in the cavity and the hydrodynamic pressure distribution along the wetted part of the panel. The hydroelastic problem is solved within the Wagner approach. The effect of gas compressibility on the elastic behaviour of the corrugated elastic panel is investigated. It is shown that the pressure in the gas cavity and elastic deflections grow beyond all bounds for the panel of infinite length and are finite if the panel is of finite length. The present model is relevant for the strength assessment of the cargo containment system (CCS) in the tanks of LNG carriers.

1. Introduction

Sloshing is a very important practical problem in the design of the cargo containment system (CCS) of the liquefied natural gas (LNG) tanks of membrane type. Within the membrane type concept the LNG is kept liquid at very low temperature (−165 °C) by complex insulation system which is attached to the ship structure. There exist today two main types of CCS and they are shown in Fig. 1. Both systems are structurally very complex and involve different types of materials (plywood, perlite, invar, stainless steel, foam, glue, etc.) which are connected together and attached to the hull structure. At the same time, on the side in contact with the LNG, both systems have non-flat surfaces (corrugations in the case of Mark-III system and the raised edges in the case of NO-96 system) so that the modelling of the fluid flow becomes extremely complex. The fundamental role of CCS is to keep the LNG at the required temperature and the choice of the material which is used for its construction is mainly driven by this requirement. This means that CCS has no particular role for tank structural strength and the only structural requirement for CCS is to withstand the LNG loading. In the past the LNG ships were allowed to sail either in full or empty conditions which made the structural design of the CCS relatively simple because no significant impact loading was possible. Due to the different market demand, today's operational requirements for LNG ships have changed and these ships are now allowed to sail at any filling level. This requirement introduces serious difficulties in the design of both the containment system and the associated ship structure. Indeed, violent sloshing motions may occur and the direct consequence is the occurrence of different impact situations which can induce the extreme structural loadings [1].

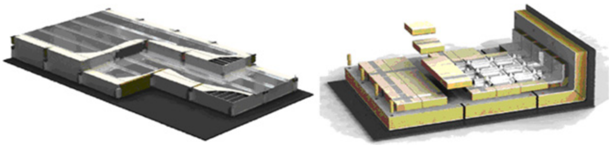
Fig. 1. Two types of containment systems NO-96 (left) and Mark-III (right).

Pure numerical modelling of coupled hydro-structure interactions during sloshing impacts is a very challenging problem from both hydrodynamic and structural sides. Indeed, even decoupled, these two problems are very difficult to model properly. Although some attempts have been made to solve the three-dimensional impact problems, the two-dimensional modelling of fluid flow is used most often. A main reason for that are the difficulties associated with the determination of the free surface flow and the exact wetted part of the structure during the impact. In addition, presence of air and possible air/fluid mixing introduce some additional difficulties. The

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three-dimensional effects of the structural response can be treated by standard finite element methods (FEM) codes provided correct characteristics of the CCS are available. The determination of the FEM characteristics is far from trivial owing to the complexity of the CCS and the associated ship structure. As far as the fluid flow is concerned, the numerical methods, which are used most often in practice, can be subdivided into the pure computational fluid dynamics (CFD) methods and the semi-analytical methods. Owing to strong variation of the free surface during sloshing, the most popular methods belong to the family of the volume of fluid technique and to the so-called smoothed particle hydrodynamics (SPH) method. SPH method has the advantage of being gridless allowing for very strong free surface variations. However, all CFD methods suffer from numerous numerical problems when it comes to the evaluation of the highly localized pressures. The mesh requirements for proper evaluation of the hydro-structure interactions during the impacts become prohibitive, and the stability of different numerical schemes is hard to ensure, especially when hydroelastic analysis needs to be performed. The numerical schemes are usually so time-consuming that it is unfeasible to use them for statistical estimates of tank responses.

Semi-analytical impact models represent another type of methods for sloshing impact problems [2]. The idea is to identify the most typical impact situations and then simplify them in order to be able to describe them with simple geometries including a few most important physical parameters only. In view of all the assumptions and uncertainties in the estimation of the sloshing impact situations, the two-dimensional approximation of the fluid flow during impact phase appears to be reasonable. However, the two-dimensional assumption of the structural behaviour can hardly be justified because the CCS is extremely complex and fundamentally three-dimensional. Within the semi-analytical approach, the three-dimensional effects can be taken into account using the so-called strip technique, which consists of considering the fluid flow as two-dimensional in each strip and considering the structure as three-dimensional. In this way it is possible to couple the semi-analytical two-dimensional models with general three-dimensional structural software. These semi-analytical models of sloshing impacts which include the entrapment of the gas cavity due to the presence of the corrugations are the main subject of the present paper.

In calculations of the tank wall response to such sloshing impacts, flexibility of the containment system might be important. The problem should be solved as a coupled problem of hydroelasticity, where the hydrodynamic loads and elastic deflections of the containment system have to be determined simultaneously. This problem was studied in [3] for compressible jet impact onto an elastic panel without corrugations. Approximate solutions of the corresponding three-dimensional problems were investigated by Khabakhpasheva [4].

The inner surfaces of the containment systems Mark-III and NO-96 are not flat. The corrugation of Mark-III system are to reduce the thermal stresses in the panel. The corrugations modify the hydrodynamic loads during fluid impact and may increase/decrease the bending stresses in the containment system. The effect of raised edges of NO-96 system on the bending stresses in the main panel was studied in [5]. The NO-96 corrugations were modelled as rigid short plates (tongues) which are perpendicular to the main elastic panel. The gas trapped between the two tongues was assumed to be mixed instantly with the fluid just after the impact instant. The gas-fluid mixture was modelled as a fictitious compressible media with a reduced sound speed.

A two-dimensional flat panel with two identical corrugations, which are those of the Mark-III containment system, is considered here (see Fig. 2). The present analysis of fluid impact onto such an elastic panel is similar to that by Korobkin and Khabakhpasheva [6], where wave impact onto an elastic plate without corrugations was studied. The Wagner approach for the hydrodynamic part of the problem and the normal mode method to describe the elastic plate vibrations were used in [6]. Impact of a rigid body with attached cavity on a liquid free surface was studied by Korobkin [7,8] and liquid impact onto a curved rigid surface was studied by Ellis et al. [9].

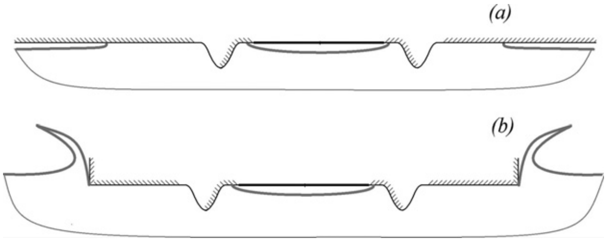

Fig. 2. Sketch of the flow caused by impact of the corrugated panel of infinite length (a) and of finite length (b).

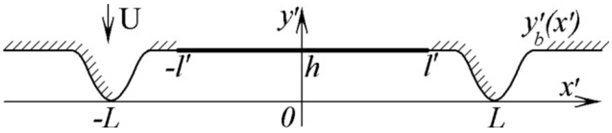

Fig. 3. Initial positions of the corrugated panel and flat free surface in the physical plane.

The problem of liquid impact on a corrugated panel is similar to that of water entry of a rigid body with a horizontal flat bottom (see Verhagen [10]), where an air pocket is formed due to the deformation of the free surface before the body comes in contact with the liquid, and the problem of a plunging breaker hitting a vertical wall (see Peregrine [11]). However, in all these problems the shapes and dimensions of the trapped air pockets come from experimental measurements or CFD calculations (see Faltinsen and Timokha [12]). In our problem, we assume that the free surface is not deformed before the panel contacts the initially flat free surface closing the cavity.

We are concerned with the early stage of the corrugated panel impact on the liquid free surface. The panel is flat with two rigid symmetric corrugations (Fig. 3). Part of the panel, $-l' < x' < l'$, is flexible and the rest of the panel including corrugations is rigid. Prime stands for dimensional variables and some physical quantities. At the initial time instant, $t' = 0$, the corrugations touch the free surface at two points $x' = \pm L$ enclosing the gas cavity. Then the panel starts to penetrate the liquid vertically with constant velocity U. It is assumed that the gas pressure inside the cavity is a function of time only. The pressure in the gas cavity depends on the cavity volume which is determined by the length of the wetted part of the panel, elastic deflection of the panel and by the shape of the cavity free surface.

Elastic deflection of the panel is described by the Euler beam equation. The beam is clamped to the main structure at $x' = \pm l$. The coupling among the fluid flow, gas pressure in the cavity and the deflection of the panel is achieved through the dynamic and kinematic conditions on the wetted surface of the panel and on the cavity surface. The Wagner approach is used in the present analysis to determine the fluid flow, pressure distribution and the free-surface shape.

2. Formulation of the problem

Entry of an elastic panel with two corrugations into an initially calm fluid is considered. The panel is symmetric with respect to the vertical axis Oy' (Fig. 3). The line $y' = 0$ corresponds to the initial undisturbed position of the free surface. At the initial time instant (t' $= 0$), the panel touches the liquid surface at two points $x' = \pm L$. The cavity filled with compressible gas is bounded by the free surface, $|x'| < L$, $y' = 0$, from below and by the panel surface from above. The height of the corrugations is h. We assume that $h/L \ll 1$. Then the