Wave-Impact in a sloshing tank: hydroelastic challenges

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Wave-impact in sloshing flows is an important issue for the safety of the Liquefied Natural Gas (LNG) carriers. Although LNG tanks have filling restrictions, they must be able to operate at any filling depth. The full understanding of the physical phenomena and the accurate evaluation of the local loads in sloshing-induced slamming events occurring in completely, partially or barely filling conditions, is a challenge of the research field. Violent free-surface motions in a sloshing tank generally occur when the energy spectrum of the ship motion is focused in the frequency region close to the lowest sloshing mode of the tank. Slamming events may occur originating impulsive and large local loads that undermine the integrity of the structure.

Depending on the local flow features before the impact, several and complex scenarios can characterize the physical evolutions of a wave impact in a sloshing flow. For example, when the impact angle between water and body is small, air entrapment may occur making important the compressibility of the air and its interaction with the free surface. In contrast, for an incipient breaking wave approaching a vertical wall, flip-through event may happen causing localized and large loads without any air-entrapment or flat-impact may occur. In all these cases, when the typical temporal duration of the local load is comparable with the lowest natural period of the structure, hydroelasticity matters affecting the integrity of the structure. Present research investigation pursues the experimental study about the kinematic and dynamic features of a wave impacting a rigid vertical wall of a 2D sloshing tank in shallow water conditions. Previous papers (1), (2), (3), have emphasized how the maximum pressure around the impact area is an unreliable indicator of the maximum load (with value of the standard deviation up to 50%), because of the stochastic behaviour of the impact phenomena. Here, the strain distribution along a deformable aluminum plate inserted in a rigid vertical wall of a sloshing tank has been measured to characterize the features of the local loads.

Hydroelastic design and set-up of the experiment The same plexiglas tank used in (2) and (3) has been adopted for the present experiments. It is reinforced with steel and aluminum structure to allow tests in depressurized conditions. A global view of the tank is shown in 1. The following geometry has been examined: length L $=$ 1m, height H $=$ 1m,

Figure 1:
Experimental set-up for the sloshing-tank experiments.

width b $= 0.1$m. Finally, a filling depth d $= 0.123$m has been used. The transversal aspect-ratio of the tank ensures an almost 2D flow in the middle vertical plane of the tank unless flow instabilities are excited. An *ad-hoc* left vertical wall of the tank has been designed and built to realize a proper scaling of the structural properties. More in detail, an aluminum plate, whose vertical size is scaled with respect to the one of the typical panel used in a Mark III containment system

(4), has been inserted in an extremely rigid stainless steel wall. The plate, with vertical length of 9 cm, is located at 13 cm from the bottom of the tank. It has been clamped to the steel frame in correspondence to the vertical ends, while the lateral ends are left free. In this way, supposing a two-dimensional evolution of the hydrodynamic load, a double-clamped beam behaviour can be assumed. Preliminarily, sizes, thickness and structural properties of the deformable plate have been fixed in order to reproduce the lowest structural natural wet frequency of the prototype panel system (4). To this purpose geometric and Froude scaling have been satisfied using a scale factor 36. An hexapod system 'MISTRAL' (made by Symetrie), has been adopted to force a pure sway sinusoidal motion of the tank. A suitable vacuum pump was used to vary the ullage pressure inside the tank between 1 bar, i.e. atmospheric pressure, down to 25mbar. In the arrangements used for the present experimental investigation, the tank was equipped with two differential pressure probes along the rigid vertical wall, and eight strain gauges along the deformable aluminum plate. Preliminarily to determine the dynamic response of the strain gauges, two miniaturized accelerometers have been mounted next to two strain gauges and the corresponding signals have been compared. Finally, an accelerometer has been put on the vertical rigid wall to check its rigidity as well as the global motion of the tank. The signals of the transducers were recorded through an acquisition system with a sample rate of 20 kHz. During the tests, visualizations of the local flow during the evolution of the phenomenon were performed through a high-speed digital video camera (with sample rate of 4 kHz), while a global view of the sloshing flow was recorded through two slow digital cameras (with a sample rate of 100 Hz). A common reference signal is used to synchronize the images with the analog signals of the transducers. Three different impact scenarios have been considered: a) flip-through, b) impact with small air-entrainment, c) impact with large air-entrainment. For the last two cases, the influence of the Euler number, i.e. of the ullage pressure inside the tank, will be investigated as a future activity. Here, the main emphasis will be given to the results of the case a), postponing to the Workshop the discussion of the cases b) and c).

Hydroelastic feature during a flip-through event. The first flip-through event realized in the present experiment happens during the 4^{th} cycle of oscillation of the tank, just after an impact phenomenon with air-entrapment. As well known in literature (5), the evolution of a flip-through is characterized by three different stages: wave advancement, focusing with formation of a jet and jet evolution. In the following, figures 2-5 will be used to discuss the dynamic and kinematic evolution of the phenomenon. In each figure, the image on the left column gives a snapshot of the wave evolution at the time instant t, as well as the values of the horizontal (un) and vertical (vn) component of the velocity associated to the Lagrangian markers in solid ($n = 1$) and dashed ($n = 2$) lines. Here the horizontal and vertical axes represent the distance from the left lateral wall and from the tank bottom, respectively. On the right column, the spatial distribution of the displacement along the centerline of the elastic plate (top panel), the time history of the strain at the center point of the plate (middle panel) and the time history of the pressure recorded by the probe on the rigid wall, i.e. located at 5 cm from the bottom of the tank (bottom panel), are reported. Finally, in each figure, the bullet in each temporal-record plot indicates the time instant corresponding to the image and to the displacement distribution along the elastic plate reported. The images shown in figures 2 and 3 highlight the wave advancing towards the wall with an increasing vertical speed of the wave trough. The values of the velocity components of the Lagrangian markers confirm the theoretical expectations: while the horizontal component of the velocities ($u1$ and $u2$) is almost constant, the vertical component ($v1$ and $v2$) increases. As the wave trough reaches one third of the vertical size of the deformable plate, i.e 160 mm (image of figure 3), the elastic plate deforms because of the hydrodynamic load (almost quasi-static) acting on it.

During the focusing stage, the sudden increase of the hydrodynamic load (see the pressure time history in figure 4 or 5) induces before the largest displacement distribution of the plate (top-right panel of figure 4) and then its elastic return in the opposite direction (top-right panel of figure 5).

At this stage, the largest hydroelastic interaction occurs: the hydrodynamic load forces the maximum strain of the elastic wall (bullet in the middle-right panel of figure 4). The consequent elastic return causes the further increase of the hydrodynamic load up to the maximum value (bullet in the bottom-right panel of figure 5).

Starting from this time instant, free vibration phase of the elastic plate occurs. However, while a constant and almost linear decay of the time history of the strain recorded in the middle point of the elastic plate is observed, pressure load on the rigid wall is strongly affected by the hydroelasticity of the plate, inducing its amplification. The free-vibration phase dominates the following evolution of the phenomenon, in particular the stages related to the formation and evolution of the jet. Here the pressure behavior is affected by the deformation of the elastic plate, being the two signals out of phase. A deformation of the panel towards the fluid causes a compression wave which induces an increase of the pressure signal at the rigid wall; in contrast the pressure decreases when the displacement of the panel is in the opposite direction.

At the end of the jet evolution stage, the amplitude of the elastic oscillation is almost null, and the pressure on the rigid wall becomes close to the hydrostatic value.

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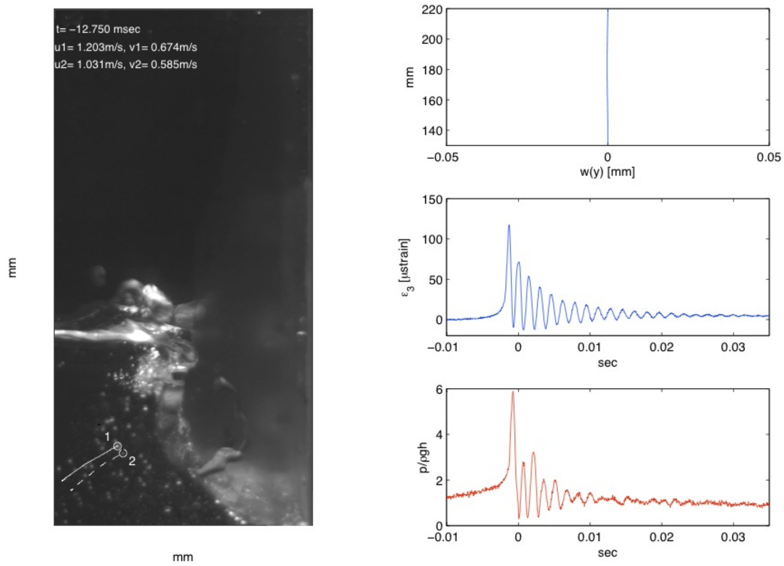

Figure 2:
Left: snapshot of the wave evolution at the time instant t and horizontal (un) and vertical (vn) velocity component of two Lagrangian markers in solid ($n = 1$) and dashed ($n = 2$) lines. Right: displacement along the centerline of the elastic plate (top), time history of the strain at the center point of the plate (middle) and the time history of the pressure recorded by the probe on the rigid wall, i.e. located at 5 cm from the bottom of the tank (bottom).

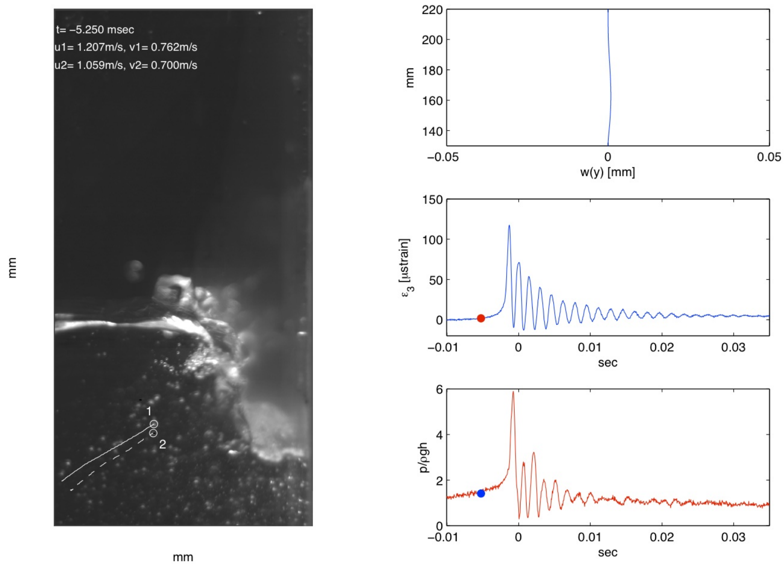

Figure 3:
See caption of figure 2.

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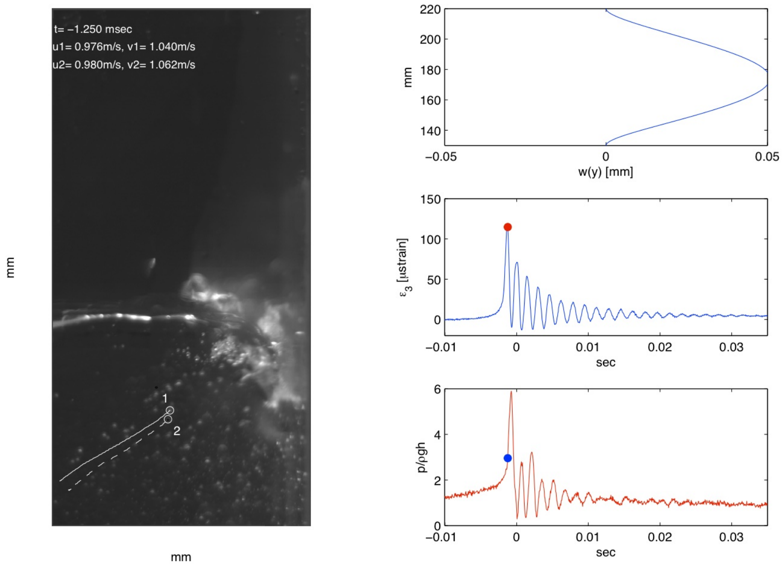

Figure 4:
See caption of figure 2.

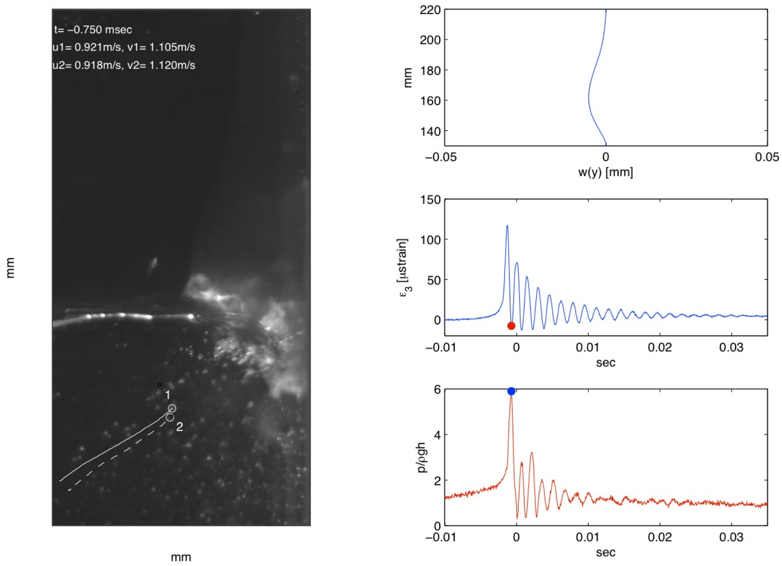

Figure 5:
See caption of figure 2.

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