# Evolution of the air-cavity during a wave impact

Claudio Lugni[1], Massimo Miozzi[1], Maurizio Brocchini[2]
[1]*INSEAN, The Italian Ship Model Basin, Roma, Italy*
*E-mail: c.lugni@insean.it, m.miozzi@insean.it*

[2]*Dipartimento ISAC, Università Politecnica delle Marche, Italy*
*E-mail: m.brocchini@univpm.it*

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SUMMARY. An investigation of the kinematical evolution of the wave impact against a vertical wall is proposed in the present paper. To this purpose 2D sloshing experiments in shallow–water conditions have been performed. The main emphasis of the study is given to the role of the ullage pressure, i.e. the constant pressure existing inside the tank, on the evolution of the air cavity entrapped during the impact of the breaking wave against the vertical wall.

## 1 INTRODUCTION

Violent wave–structure interaction is an important topic in several fields of the engineering.

In the context of coastal engineering, the impact of steep water waves can result in damage or collapse of structures. In particular failure of vertical breakwaters and coastal defences has led to much attention been given to the pressure distribution which occurs when steep storm waves meet sea walls. Both experimental and theoretical studies have highlighted the fundamental role of the very large impact pressures which are impulsively exerted on sea walls [1]. In particular cracks, which may be the gaps between neighboring blocks of the structures, can be highly solicited by intense impulsive pressures. The induced wave forces can cause considerable lateral stresses on the constituents of a sea wall, affecting even the static stability of the structure. A comprehensive review of research concerned with water wave impacts on walls is proposed in the review of Peregrine [1]. Other extensive sources of information on wave impact on walls can be found in the reports of the EU MAST funded projects Monolithic Coastal Structures (MCS) and PRObabilistic VERtical Breakwaters (PROVERBS, see [2]). In all the mentioned conditions extremely large impact pressures can be measured which largely exceed those associated with the internal pressure of the waves. Recorded pressures are in the order of 10–100 times the hydrostatic pressure associated with the impacting wave height, depending on the impact conditions [3, 4, 5, 6]. This clearly suggests that the largest pressures are essentially due to the flow inertia, gravity effects being negligible. The shape of the impacting wave has a significant effect on wave impact pressure exerted on vertical walls [5]. However, because of the experimental difficulties associated with recording the details of the impact (for reliable recording of impact pressure peaks sampling rate of some kHz are needed), only relatively few research works have been dedicated to the analysis of the relationships between the wave shape and the impact pressure magnitude and distribution. Notwithstanding these difficulties Oumeraci et al. [7], on the basis of methodic analyzes of impact pressure histories and of the corresponding high–speed video pictures (200Hz), proposed a classification of impact modalities which seems to encompass all possible conditions. The position of the break point not only influences the peak of the impact pressures but also determines the way in which the air between structure and wave is expelled, entrapped and/or entrained [8]. Aeration and turbulence in the water also occurs from the breaking of previous waves and tend to be non-uniform. They both introduce three–dimensionality.

Air is far more compressible than water and the presence of significant quantities of air complicates both the impact process and the way in which shock pressures propagate into water–filled cracks [9], a phenomenon detrimental to the survival of both masonry structures and natural cliffs. In fact, though aeration has generally been thought to soften the impact pressures, it also introduces strong gradients of sound velocity, and it seems possible that these could focus pressure waves from wave impact, as is seen with shock waves in a gas incident on low velocity bubbles ([10]). Field measurements [11] have shown that high aeration levels coincide with long rise times and lower pressures whereas short duration high peaked pressures were also observed, but they occur at lower aeration levels. Recent unpublished results show that air cushioning of wave impacts is counteracted, for pressures significantly greater than atmospheric, by the greater contraction of the air pocket leading to increased pressure maxima [12, 13]. This clearly suggests that the largest pressures are essentially due to the flow inertia, gravity effects being negligible.

In the naval context, the knowledge of the flow features occurring during the violent liquid motion inside confined spaces [14], is a key issue for the safety of LNG (liquid natural gas) carriers. Since these ships have to operate in various filling conditions of their tanks, it is important to properly understand the main features of the phenomena appearing with the tank almost completely [15], partially [16] or barely filled [17]. In particular violent free surface flows may appear when the energy spectrum of the ship motion is focused in the region close to the lowest natural tank mode. Then, large slamming loads [18] may occur undermining even the integrity of the structure. In this condition a proper prediction of the impulsive loads and of its duration may matter for a suitable estimation of the hydroelastic effects. For example, membrane-type tanks may have a relevant structural natural period at full scale close to $10$ms, i.e. comparable with the characteristic period of the wave impact. Differently, steel structures in OBO carriers may have a larger relevant natural period (say $50$ms), so that pressures caused by the impact of steep water-waves, appear as an impulsive force. A complex flow may characterize the evolution of a slamming phenomenon. For instance, when the initial impact angle is small, compressibility may matter as a consequence of the air entrapped. A mutual interaction between gaseous and liquid phases may occur. Increasing the pressure inside the gaseous cavity may cause its oscillation and then its collapse with the formation of a mixture gas bubbles liquid. In this case the pressure inside the tank, i.e. the ullage pressure, strongly influences the appearance and the evolution of the gas bubbles during the impact. The proper scaling of the slamming loads is an open question in the design of the tank for model tests. Since sloshing involves gravity waves, it is common to satisfy the Froude scaling, so that the Froude number be the same between model and full scale. As a consequence, also the frequency of oscillation of the tank is Froude scaled. When an air-cavity is entrapped, compressibility matters. The pressure inside the tank is a fundamental quantity governing the evolution of the phenomenon: the Euler number should be then taken into due account.

The main aim of the present paper is both the experimental investigation of the kinematical flow field featuring the wave impact and the study of the effect of the ullage pressure on the evolution of the air-cavity entrapped during a wave impact caused by a sloshing event in a rigid prismatic tank.

## 2 EXPERIMENTAL SET-UP

An ad–hoc plexiglas tank, reinforced with steel and aluminium structure, has been built. A global view of the tank is shown in Figure1. The following geometry of the tank, identical to that used in [6], has been reproduced: being $L = 1$m the length, $H = 1$m the height, $b = 0.1$m the width. Finally, a filling depth $d = 0.125$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. A mechanical system forces a pure-sway motion with a sinusoidal law, $Asin(2\pi t/T)$, being A the amplitude and T the period of the prescribed motion. A suitable vacuum pump was used to vary the ullage pressure inside the tank between $1$ bar, i.e. atmospheric pressure, down to $15$mbar. In the arrangements used for the present experimental investigation, the tank was equipped with eight differential pressure probes along a vertical wall, with maximum range of linearity varying between $14$kPa up to $40$kPa. During the tests flow visualizations were performed through high–speed digital video cameras. A high–speed camera Photron Ultra was placed very close to the lateral wall of the tank, as shown in the photo of figure1, and focused to minimize perspective errors in the images. More in detail, the measurement area corresponding to $1024 \times 512$ pixels, was focused at the center

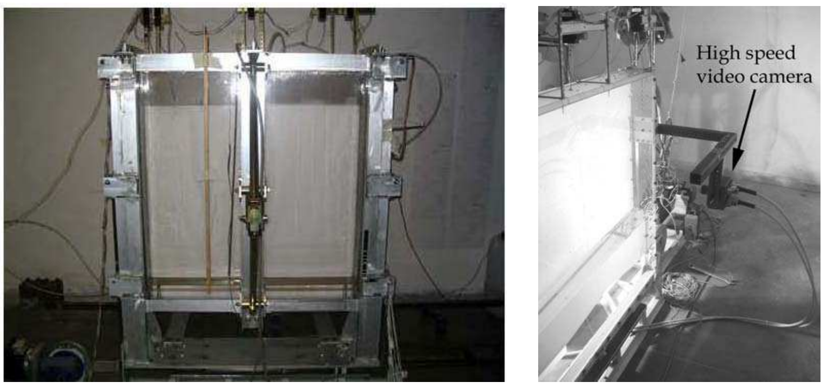


Figure 1: Sloshing tank (left panel) and Photron Ultra high speed video camera (right panel).

of the image. A target of calibration has been used both to evaluate for each run the magnification factor ($\approx$ 7pix/mm), and to check the deformation of the measurement region. A frame rate of 4000 fps was used to well capture the high velocities of the flow during the formation of the jet, as well as to capture the oscillation of the air–cavity entrapped during the impact event. To ensure synchronization, the trigger signal, used to start the camera, has been acquired by the acquisition system.

## 3 RESULTS

With the aim to understand the evolution of the kinematical flow field featuring a wave impact phenomenon, topological, kinematical and dynamical results on the wave impact are here reported (see also [6] for more details). Sloshing tests performed by varying the amplitude and the frequency of the motion of the tank, and keeping the ullage pressure at the atmospheric value, enabled identification of three different modalities of the wave impact flow.

The most spectacular event occurs when the front of the impacting wave advances toward the wall interacting with the rigid boundary before it breaks; it is nicknamed *flip-through* [1], i.e. mode *a)*. The global evolution of the free-surface inside the tank highlights the formation of an energetic jet along the wall, without any impact phenomenon occurred. A more local investigation enables identification of the details of the wave impact evolution and the occurrence of a flip–through event. The flow evolution that leads to a flip–through event is, essentially, made of three main stages: *(i)* wave advancement, *(ii)* focusing, and *(iii)* jetting. During stage *(i)* (see the left panel of figure 2) the wave front approaching the wall forces the trough to rapidly rise upward at the wall. Then, i.e. stage *(ii)* (see middle panel of figure 2), the wave front and trough move toward each other, originating an intense acceleration of the flow. Finally, during stage *(iii)* (see the right panel of figure 2) a sudden turning of the flow just in the focusing area leads to the formation of a vertical jet.

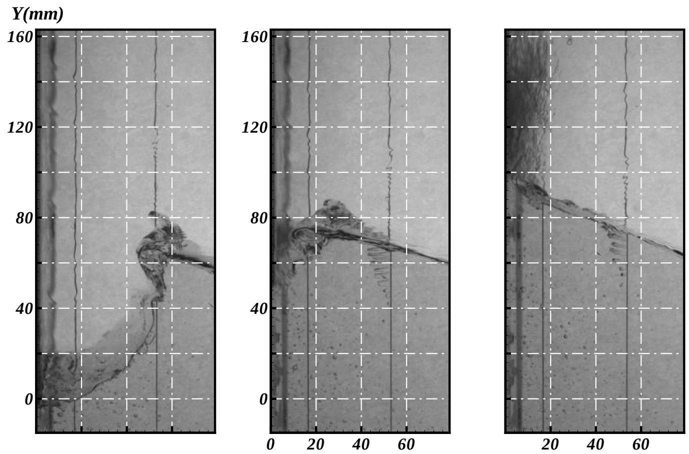


Figure 2: Sequence of a flip-through event evolution (mode *a)*).

A second modality of wave impact, i.e. mode *b)* occurs when an almost broken wave with no phase–mixing approaches the wall. In this case the most interesting feature is the formation of a small air cavity induced by the overturning of the wave crest advancing towards the wall (first two panels of figure 3). This, first separates the near–wall jet from the approaching wave face (third panel of the figure), subsequently the air cavity closes because of the meeting of the head of the jet with the almost disrupted wave crest.

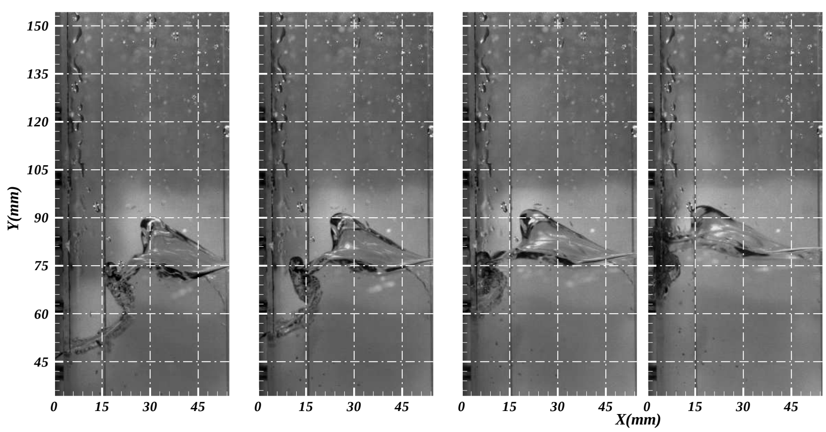


Figure 3: Sequence of the evolution of a wave impact with air-cavity (mode *b)*).

A third modality (mode *c)*) is the impact of a broken wave with air/water mixing. A turbulent flow characterizes the evolution of the wave fronts. Because of the fragmentation of the free surface (first three panels of figure 4) strong 3D effects characterize the advancing of the wave front: a flip–through event appears in front of a cushion of air–water (fourth panel), causing a damping of its evolution. A considerable mass of fluid characterizes the formation of the jet, as well as its evolution.

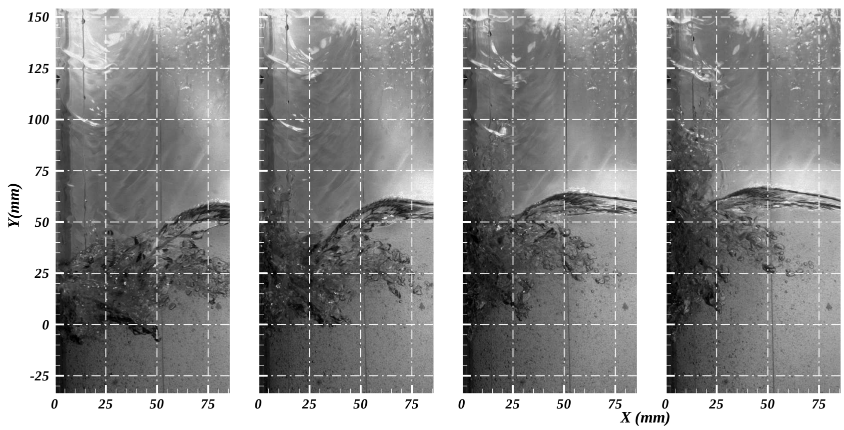


Figure 4: Sequence of the evolution of a wave impact with phase mixing (mode *c)*).

With the aim to investigate the evolution of the air-cavity entrapped during a wave impact phenomenon, in the following we investigate the influence of the ullage pressure, i.e. the constant pressure existing inside the tank at the equilibrium, for the mode *b)* wave impact. In particular, the third wave impact event appearing on the wall for a sinusoidal motion of the tank (corresponding to an amplitude $A = 3$ cm and a period of $T = 1.6$ s) has been considered. The analysis of the results presented here is based on the observations of the images of the high–speed camera and of the pressure probes. A more detailed analysis, including the results of the kinematic field around the bubble through a lagrangian Features-Tracking algorithm [19] will be presented at the AIMETA 2009 Conference.

Several modalities of evolution of the air–cavity entrapped by the breaking wave approaching the wall have been observed during our experiments. Figure 5, reporting a typical sample sequence of the air–cavity images collected during the experiments, shows the formation of the bubble and its evolution during the considered event corresponding to a ullage pressure of $900$mbar. The time histories of the pressure probes at the positions on the wall indicated by the red rectangles on each image, are also reported in the bottom–right panel. Here the dashed lines indicate the time instants corresponding to each image.

The top–left panel of the figure shows the free–surface deformation at the time instant just prior to the wave impact. The overturning wave tends to close the air–cavity before its impact with the wall. During the first stage of the impact (top–right panel) the air–cavity is quickly compressed and air escapes from the splashing wave crest: a turbulent jet is then formed and the pressure at the wall starts to increase (see bottom–right panel). At the time of the maximum pressure (top–right panel), a flip–through event is generated from the trough of the bubble, which appears as an air–water

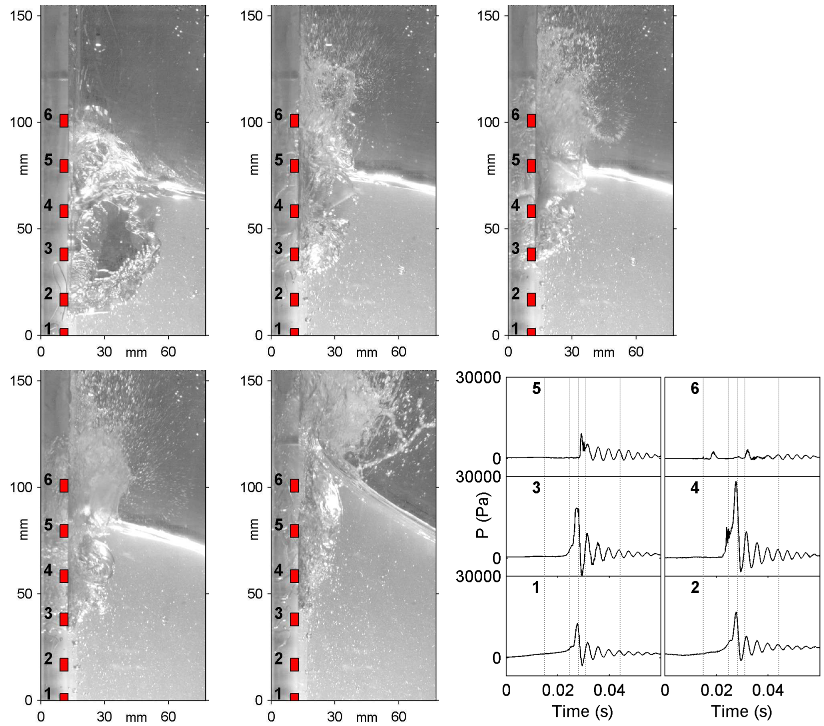


Figure 5: Sequence of images illustrating the free–surface evolution of a flip–through with air–entrapment (tank pressure: $900$mbar, camera scan rate: $4000$fps). From left to right and from top to bottom times, measured with reference at the time of the trigger signal, are: $15$ms, $25$ms, $28$ms, $31$ms, $44$ms. Time histories of the pressure transducers along the wall are reported in the right–bottom panel. The dashed lines represent the time corresponding to the previous images.

mixture. The rapid acceleration of the upward jet formed by the flip–through induces a well–shaped bubble (bottom–left panel) which starts to oscillate with a frequency of about $260$Hz. The following evolution (bottom–middle panel), shows the advection of the air-cavity induced by the upward flow. This causes stretching of the bubble and, then, variation of its frequency of oscillation. To well highlight the latter behavior, the left panel of figure 6 shows the results of the Shifting Window Fast Fourier Transform applied to the pressure time history (reported in the top subpanel of each panel) measured by sensor $4$. At the time of the image reported on the bottom–left panel of figure 5, a rather sudden jump in the frequency of oscillation, from $260$Hz to $320$Hz, is observed in the pressure time history (see also the left panel of figure 6).

When reducing the ullage pressure inside the tank, a different flow feature characterizes the evolution of the air–cavity, as shown in figure 7 for $p_{tank} = 800$mbar. A flat impact of a disrupted and three–dimensional wave crest (highlighted by the pressure peak occurring around t$= 0.01$s in the pressure time histories of the transducers $4$ and $5$, see the bottom–right panel of figure 7) causes a splitting of the jet in opposite directions.

The upward jet is almost turbulent and three–dimensional. The downward jet, together with the advancing and more compact wave front, causes a compression of the air cavity with some of the

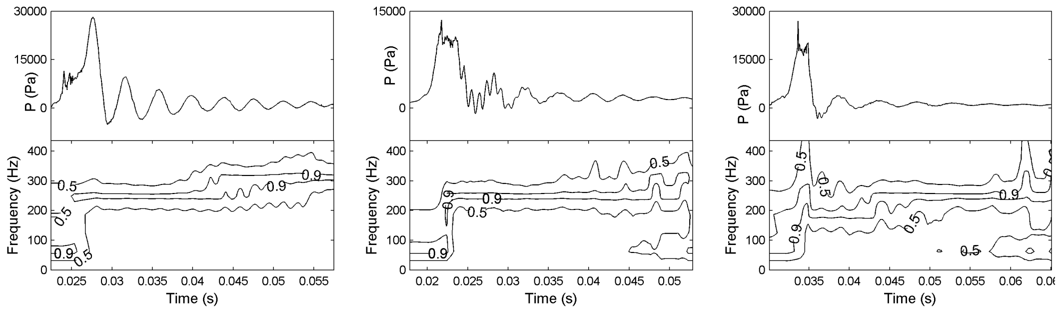


Figure 6: Time evolution of the frequency of oscillation of the bubble as obtained by the Shift Windowing Fast Fourier Transform applied to the pressure signal of sensor $4$ (reported on the top of each panel). From left to right the results related to the internal pressures of the tank $900$, $800$ and $400$ mbar respectively, are reported.

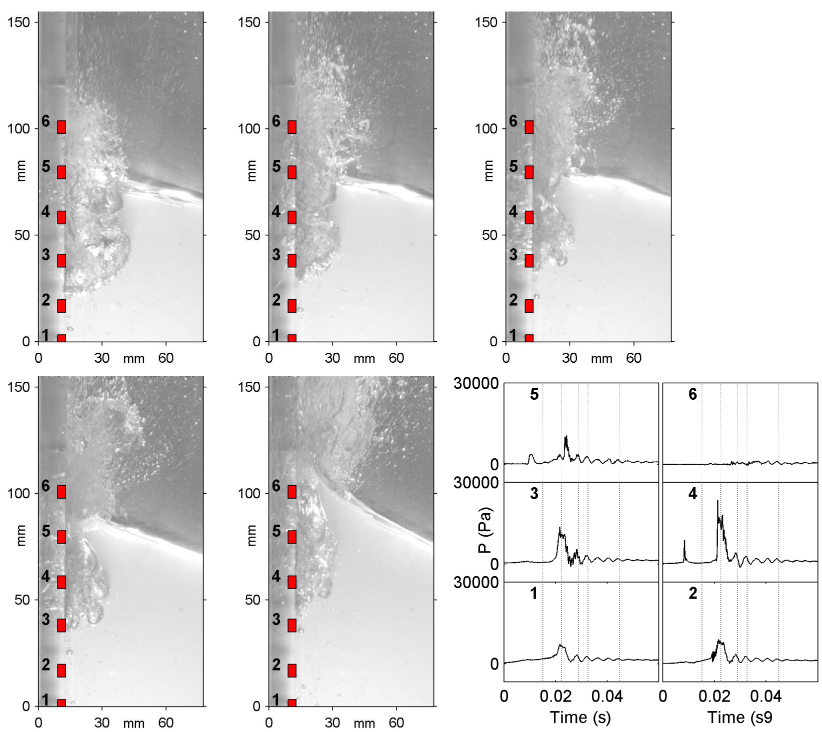


Figure 7: Sequence of images illustrating the free–surface evolution of a flip–through with air–entrapment (tank pressure: $800$mbar, camera scan rate: $4000$fps). From left to right and from top to bottom times, measured with reference at the time of the trigger signal, are: $15.5$ms, $20$ms, $24$ms, $28$ms, $36$ms. Time histories of the pressure transducers along the wall are reported in the right–bottom panel. The dashed lines represent the time corresponding to the previous images.

air escaping upward (top–right panel of figure 7). The wave front which follows appears to be split into two parts. The lower one tends to form a well–shaped bubble (top–right and middle–left panels) while the upper one resembles a local wave trough evolving in a strong-runup. The bubble oscillates around its mean position (close to that of sensor $4$) with a constant frequency approximatively equal to $245$Hz. In this case (bottom–left panel) the bubble is slightly advected upwards, its frequency of oscillation being unaltered as highlighted in the time history of the oscillation frequency, reported in the middle panel of figure 6.

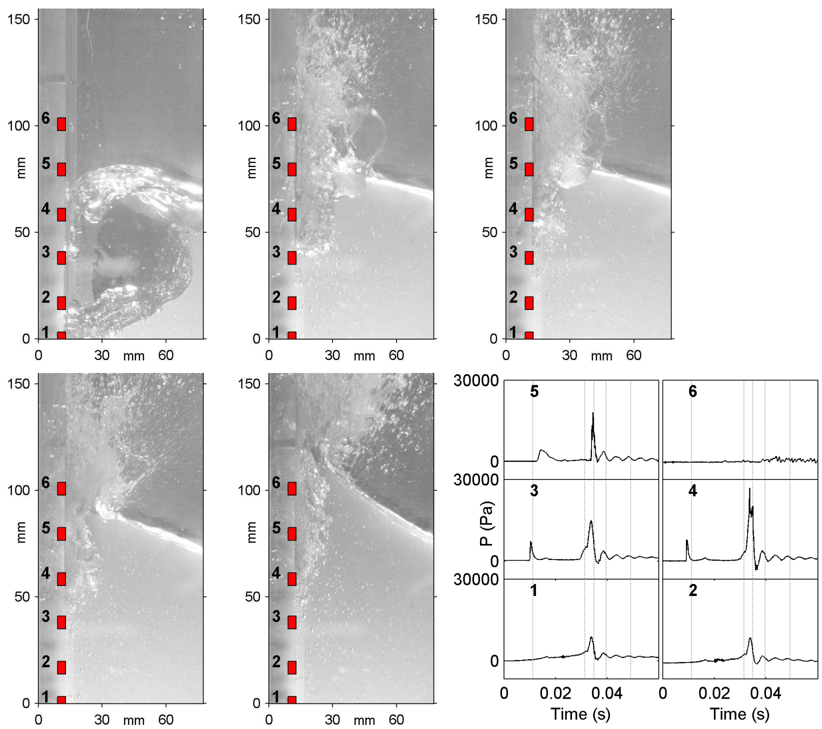


Figure 8: Sequence of images illustrating the free–surface evolution of a flip–through with air–entrapment (tank pressure: $400$mbar, camera scan rate: $4000$fps). From left to right and from top to bottom times, measured with reference at the time of the trigger signal, are: $11$ms, $31.5$ms, $35$ms, $40$ms, $49$ms. Time histories of the pressure transducers along the wall are reported in the right–bottom panel. The dashed lines represent the time corresponding to the previous images.

No flip–through event has occurred in this case. As a consequence the maximum pressure peak is strongly reduced, varying from $30$kPa for $p_{tank} = 900$mbar to approximatively $15$kPa for $p_{tank} = 800$mbar. A well–defined bubble is formed at the wall, with no downward jet (middle panels). Finally, the evolution of the jet induced by the impact, causes a strong stretching of the bubble (bottom–left panel). As a consequence, the frequency of oscillation changes as highlighted by the time history of the frequency in the middle panel of figure 6. The stretched bubble seems to be rather stable as highlighted by the oscillation measured by the pressure sensors $5$ and $6$, characterized by a very small decay.

One further modality of formation and oscillation of the bubble is observed in correspondence of an ullage pressure of 400mbar. The flat impact of the irregular crest (top panels of figure 8) of the advancing wave anticipates the formation of a flip–through event. More in detail, because of the splitting of the wave front induced by the flat impact, a bubble is formed on the lower part (middle–left panel). At the same time, a flip–through event appears on the trough of the bubble. Due to the synchronization of the phenomena involved, a weak bubble is formed (pressure time histories in the bottom–right panel of figure 8). The latter is rapidly advected by the upward jet, which causes its stretching and partial fragmentation, as shown on the bottom right panel of figure 8 and confirmed by the quick change of frequency in the time evolution shown in the right panel of figure 6.

## 4 CONCLUSIONS

The kinematical evolution of the wave impact against a vertical wall inside a sloshing tank has been studied in the present paper. Three different modalities of the wave impact flow have been identified: flip through event (i.e. *mode a)*), impact with air-cavity entrapment (i.e. *mode b)*) and, finally, impact of a broken wave with air–water mixing (i.e. *mode c)*). In particular for the *mode b)* the effect of the ullage pressure, i.e. the constant pressure existing inside the tank at the equilibrium, on the evolution of the air cavity has been investigated.

Preliminary analyzes enabled the identification of different flow features characterizing the evolution of the air cavity. In particular, by decreasing the ullage pressure the air entrapped is largely compressed inducing a smaller size of the oscillating bubble and then a smaller amplitude of the pressure oscillation. Further details on the ongoing investigation will be given at the AIMETA 2009 Conference.

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