NONLINEAR WAVE SLOSHING IN A RESERVOIR: EXPERIMENTAL AND NUMERICAL RESULTS

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Abstract. *The present work presents a shaking table facility for wave sloshing analysis and validation of numerical simulations. The table consists of a platform connected to an electrical motor, which is controlled by a computer, leading to horizontal displacements and generating free-surface disturbances at the reservoir. Electronical interfaces are used for digital control of the table and implemented under the Labview environment. Free-surface profiles are registered by a digital camera. Results show a good agreement between experimental and numerical profiles.*

Keywords*: Free-surface flow; wave impact; finite volume method.*

1. INTRODUCTION

Energetic waves can be formed when partially filled liquid storage tanks are shaked under certain conditions, causing large wave impacts at the walls of the reservoir. These free-surface flow phenomena – known as wave sloshing – is a classical eigenvalue problem in fluid mechanics. In the past, scientists such as Poisson, Rayleigh and Kirchhoff investigated this theme; more recently books have been published on that subject (Faltinsen and Timokha 2009, Ibrahim 2005). These violent wave impacts have been registered on vehicles subject to large accelerations/decelerations and to harmonic loads of high amplitude, which can reach resonant modes. In such cases wave reflection at the walls induces hydrodynamical forces that may cause structural damage or hazardous destabilizing effects.

Violent and brief wave impacts have been studied by Cooker and Peregrine (1992) focusing on the pressure measured on a vertical wall. The pressure distribution presents a double peak profile in time, the first one due to the inertia of the fluid acting on a very short period of time (which may last only some milliseconds); the second peak is due to hydrostatic pressure created by the downward wave motion just after the maximum run up. Sloshing induced loads can be divided principally into non-impulse and impulse dynamic pressures. In case of a shallow filled and large excitation tank motion, a vertical front may be generated resulting on a very large impact on the tank walls. On the other hand in a nearly full compartment a progressive wave may cause stress acting on the roof of the tank. The impact is localized in time and space, with a high pressure gradient acting on a very small scale of time. These characteristics turn sloshing into a complex situation which requires fine mesh grids and small time steps for numerical models in order to avoid inaccurate results and numerical instabilities.

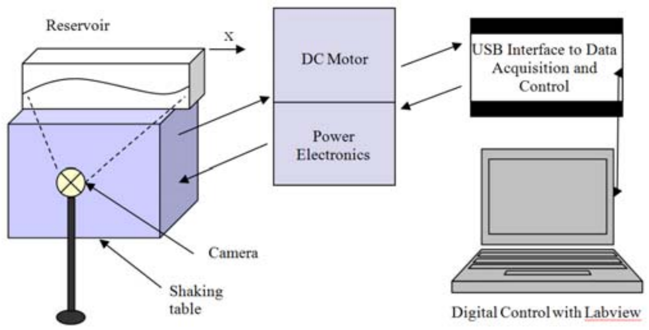
Recent references for sloshing flows include: Godderidge *et al.* (2009), who studied a near resonant sloshing flow in a rectangular tank in order to compare a homogeneous and inhomogeneous multiphase approach for fluid density and viscosity in a commercial CFD code; Nicolato and Moreira (2009), who implemented geometry optimizations to the reservoir aiming to reduce wave impact at the walls; Attari and Rofooei (2008), who studied the lateral response of a single degree of freedom structural system containing a circular cylindrical tank under harmonic and earthquake excitations; Chen *et al.* (2008), where sloshing in a rectangular tank excited by horizontal harmonic motion is assessed numerically at different filling levels and excitation frequencies; Yonghwan (2007), who considers the experimental and numerical observations of strongly nonlinear sloshing flows in ship cargo and their coupling effects with ship motion; Lee *et al.* (2006), who studied sloshing flows numerically in a LNG (liquefied natural gas) storage tank; Bredmose *et al.* (2003), who analyzed experimentally and numerically the generation of nonlinear waves in a rectangular reservoir.

In order to prevent structural failure, extensive experimental and theoretical studies have been undertaken. For instance, NASA design criteria are based on subdividing the container by longitudinal walls or installing baffles. Gavrilyuk *et al.* (2006) demonstrate fundamental solutions of linearised problems on fluid sloshing in a vertical circular cylindrical tank having a thin rigid-ring horizontal baffle. Craig and Kingsley (2006) and Cho *et al.* (2005) illustrate some strategies for preventing the impact at walls.

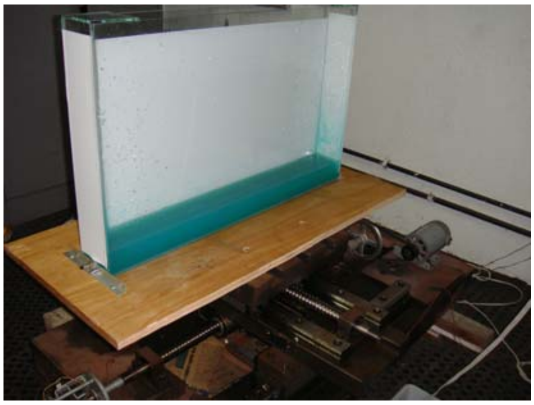
This work aims to develop experiments and numerical simulations on wave sloshing in a rectangular reservoir. A shaking table facility is built in order to validate the numerical simulations. Free-surface profiles are registered by a digital camera and compared with the equivalent numerical results. Data are also collected from a pressure transducer fitted into the tank wall.

2. EXPERIMENTAL SET UP

The shaking table facility consists of a steel structure with dimensions 1.5 x 1.0m^2 with two electrical motors which control the two-degrees of freedom system. Each motor is connected through pulleys to endless screws with recirculating sphere mechanisms. Two rectangular glass tanks - namely N1 and N2 - with internal dimensions 390 x 194 x 265mm^3 and 800 x 100 x 400 mm^3 (length x width x height) were built and fixed with its length parallel to the *x*-axis. Both reservoirs were sealed in order to protect the electrical components from water exposure. In this work displacements are allowed to occur in the *x*-direction. Figure 1 depicts the experimental set up and the shaking table with tank N2 on it.



(a)



(b)

Figure 1. Scheme of the experimental set up (a) and the shaking table facility with tank N2 (b).

A power electronic circuit was built in order to drive the electrical motors. This consists of Semikron semi-drives and IGBT devices disposed in a full bridge configuration, all mounted in a circuit board. A second circuit board was built to convert analog signals (supplied by the computer) into PWM (Pulse Width Modulation) type signals which trigger the IGBT's. The maximum switching frequency of these devices was fixed in 2.0kHz. Finally an auxiliary module (National Instruments USB-6001) was used as an interface between the two circuit boards and the computer. To record the images of the experiments, a 33 frames per second digital camera was used.

The table displacement was implemented with a control program in an open loop strategy developed in the Labview environment. The program can be resumed in the following modules.

- Reference generation: Voltage sinusoidal references were applied in order to induce harmonic horizontal displacements at the table according to,

$$x(t) = 11 \sin (5.236\, t), \tag{1}$$

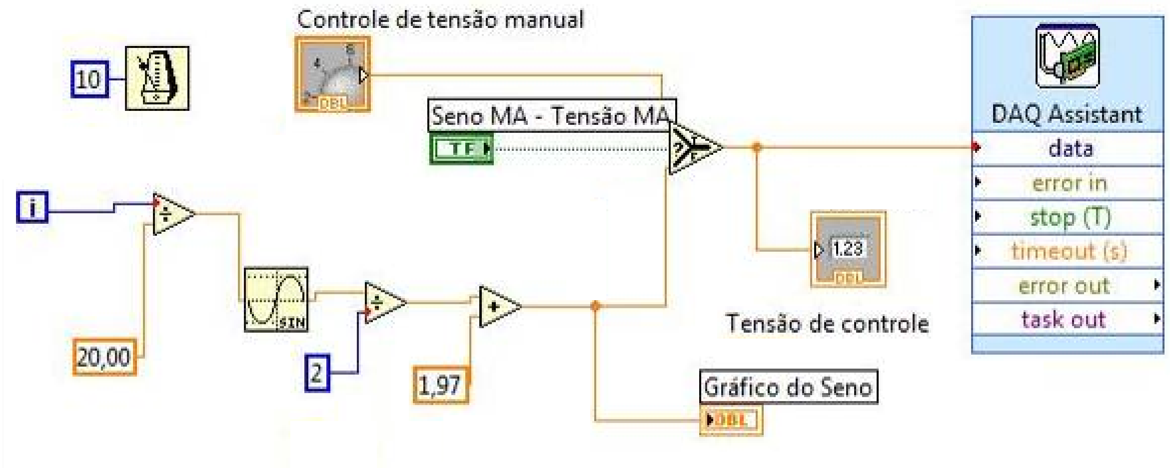
$$x(t) = 90 \sin (1.885\, t), \tag{2}$$

with x expressed in mm. Equations (1) and (2) correspond to the x-displacements imposed on experiments N1 and N2. A displacement amplitude of 11mm (90mm) with a frequency of 0.83Hz (0.3Hz) is then achieved. The PWM duty cycle can also be adjusted manually.

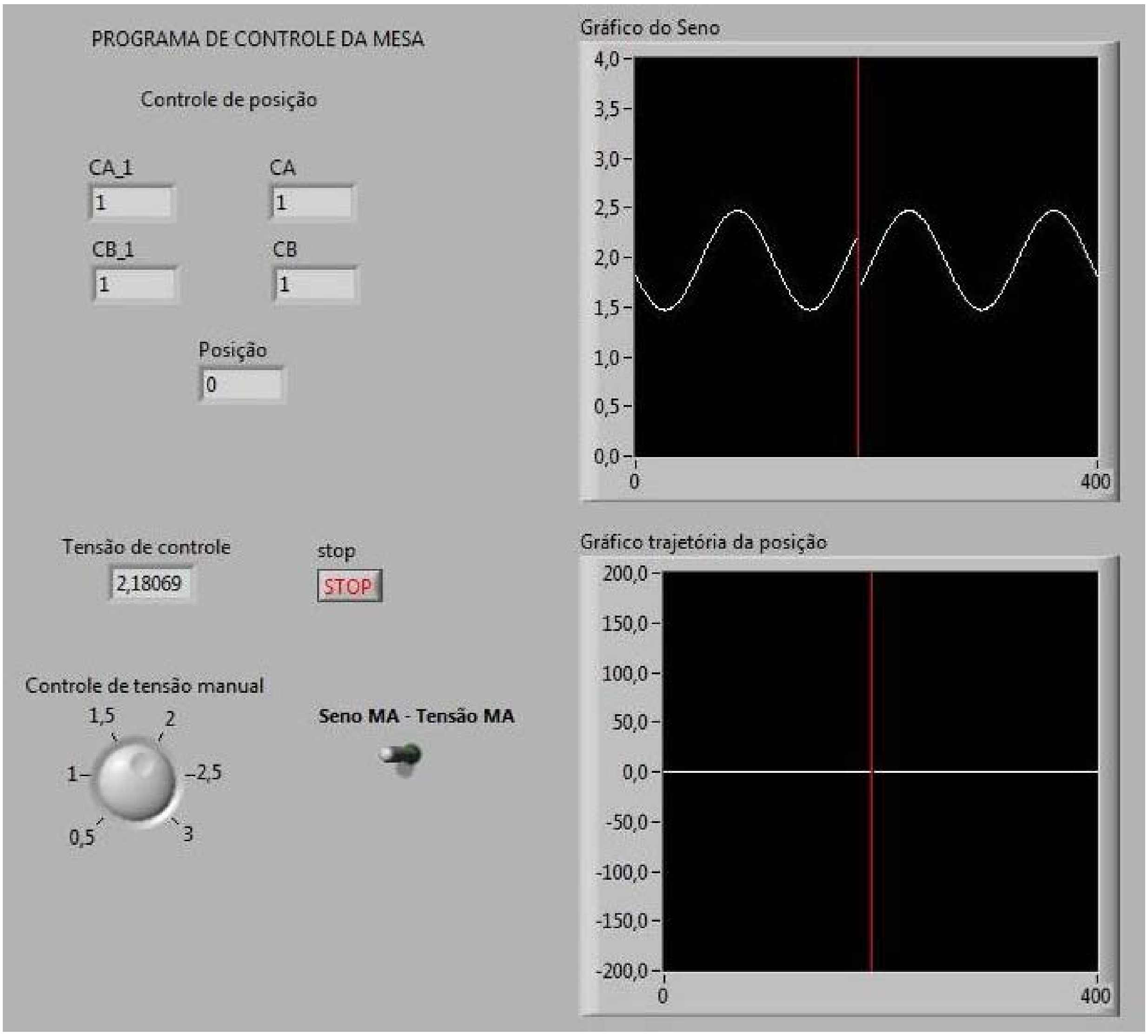
- Output signal: The DAQ assistant block is programmed to send through an analog output channel of the USB interface the electric signal to the PWM circuit generator of the second auxiliary board (see Fig. 2a).
- Graphical interface: A graphical window of the movement reference, the manual control knob, the type of operation switch and other numerical data were also implemented (see Fig. 2b).

3. INITIAL VALUE PROBLEM AND CFD MODEL

The unsteady incompressible flow with a free surface is modeled in three-dimensions with momentum and mass being conserved in the fluid domain. Cartesian coordinates are defined with the $x-z$ plane at the free surface, such that the fluid occupies the region $y \leq 0$ when at rest. To determine the fluid mixture properties a homogeneous fluid interaction model is used with a volume fraction ϕ being defined for air and water. Air is taken as an ideal gas while the liquid phase is considered incompressible. The full Navier-Stokes equation may then be written as,



(a)



(b)

Figure 2. (a) Block diagram and (b) graphical interface of the control program.

$$\frac{D(\phi\rho\boldsymbol{u})}{Dt} = \nabla\cdot(\phi\boldsymbol{T}) + \rho\phi\boldsymbol{f} \ , \tag{3}$$

where ρ is the fluid density; $\boldsymbol{u} = (u, v, w)$ is the fluid velocity; $\boldsymbol{f} = (0, -g, 0)$ is the gravitational force; $\boldsymbol{T}$ is the stress tensor, which includes the effects of pressure, expansion and viscous forces. For a Newtonian fluid with viscosity μ, bulk viscosity k and submitted to a dynamic pressure p_E , this tensor may be written as,

$$\boldsymbol{T} = -p_E\delta_{ij} + \left(k - \tfrac{2}{3}\mu\right)\nabla\cdot\boldsymbol{u}\delta_{ij} + \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right), \tag{4}$$

For the homogeneous two-phase flow,

$$\rho = \sum_{l=1}^{2}\phi_l\rho_l \ , \qquad \mu = \sum_{l=1}^{2}\phi_l\mu_l \ , \tag{5}$$

with $l=1,2$ representing water and air. Capillarity is also taken into account with surface tension between water and air at 25°C being equal to 0.007197N/m.

The continuity equation for the multiphase flow takes the form,

$$\frac{\partial(\phi\rho)}{\partial t} + \nabla\cdot(\phi\rho\boldsymbol{u}) = 0 \ . \tag{6}$$

The Neumann and Dirichlet conditions are applied at the walls. The bottom and the vertical walls are considered rigid, impermeable and with a no-slip condition such that,

$$\boldsymbol{u}_{walls} = 0 \tag{7}$$

To complete our model we assume that initially all the fluid domain is at rest while suddenly a harmonic horizontal displacement (given by Eqs. (1) or (2)) is imposed to the reservoir at time $t = 0$.

The boundary value problem is solved by the commercial CFD package ANSYS CFX release 11.0 (ANSYS 2006), which makes use of the finite volume method (Versteeg and Malalasekera 1995, Maliska 2004). The mesh was refined near the free surface and walls in order to better predict the nonlinear profile of the fluid motion. For the top of the tank the free mass transfer condition is applied. Figure 3 shows one of the computational grids used, which contains 18,480 hexahedral elements. A refined time grid is employed with time steps of 5ms for 12s of total time. All the computations were carried out on a 64 bit, 2.40 GHz Intel Quad Core processor with 8 Gb of RAM. Tests N1 and N2 have a total CPU time of $1.2\text{x}10^4$ and $4.8\text{x}10^4$s, respectively.

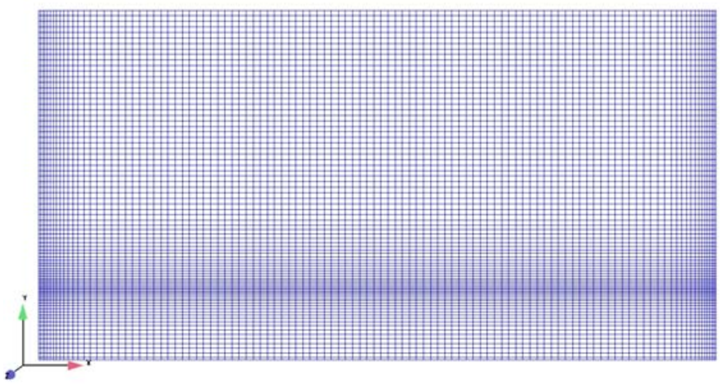


Figure 3. Computational grid.

4. RESULTS

Results for the free-surface profiles for two arrangements are presented in this section, namely N1 and N2, which follow the harmonic horizontal displacements given respectively by Eqs. (1) and (2).

4.1. N1 test

In that case disturbances generated by the sinusoidal movement causes the formation of a progressive wave which impacts at the right side of the tank at time t=2.80s (see Fig. 4, right column). The numerical computations (left column of Fig. 4) overpredict the maximum run up at the wall which may be associated to the negligence of surface tension effects in the numerical model.

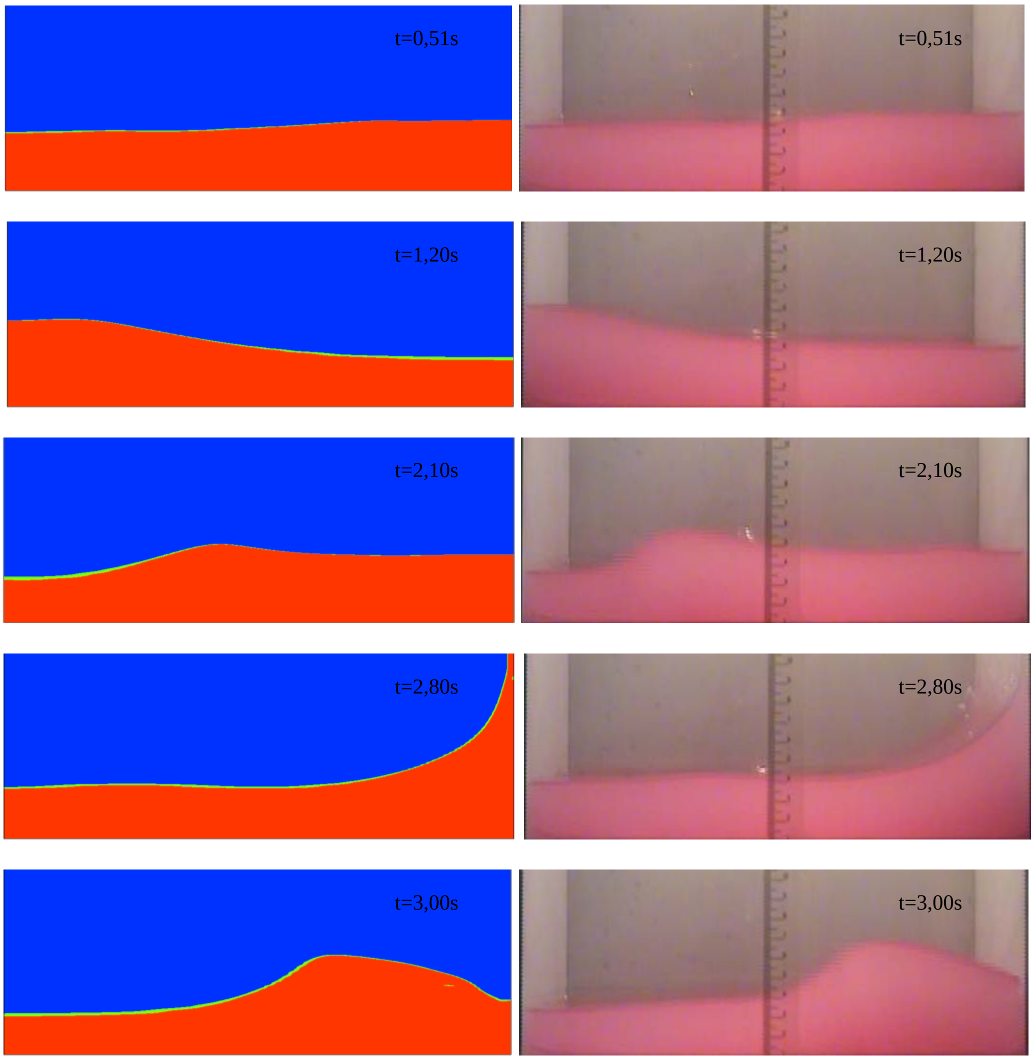


Figure 4. Comparison between numerical (left column) and experimental (right column) free-surface profiles.

4.2. N2 test

As we increase the size of the reservoir from N1 to N2, the shaking table facility fails to impose larger amplitude displacements which would generate more energetic waves. Figure 5 shows the free-surface profiles obtained when the harmonic horizontal displacement given by Eq. (2) is imposed. Disturbances are much smaller with linear waves being formed along a total time of 12s. As expected a good agreement between numerical and experimental results is achieved since nonlinearity barely affects the free surface. Preliminary results obtained from a pressure transducer installed at the N2 tank vertical wall with an imposed manual displacement shows that the double peak pressure profile commonly observed on sloshing flows can be registered (see involved red area in Fig. 6).

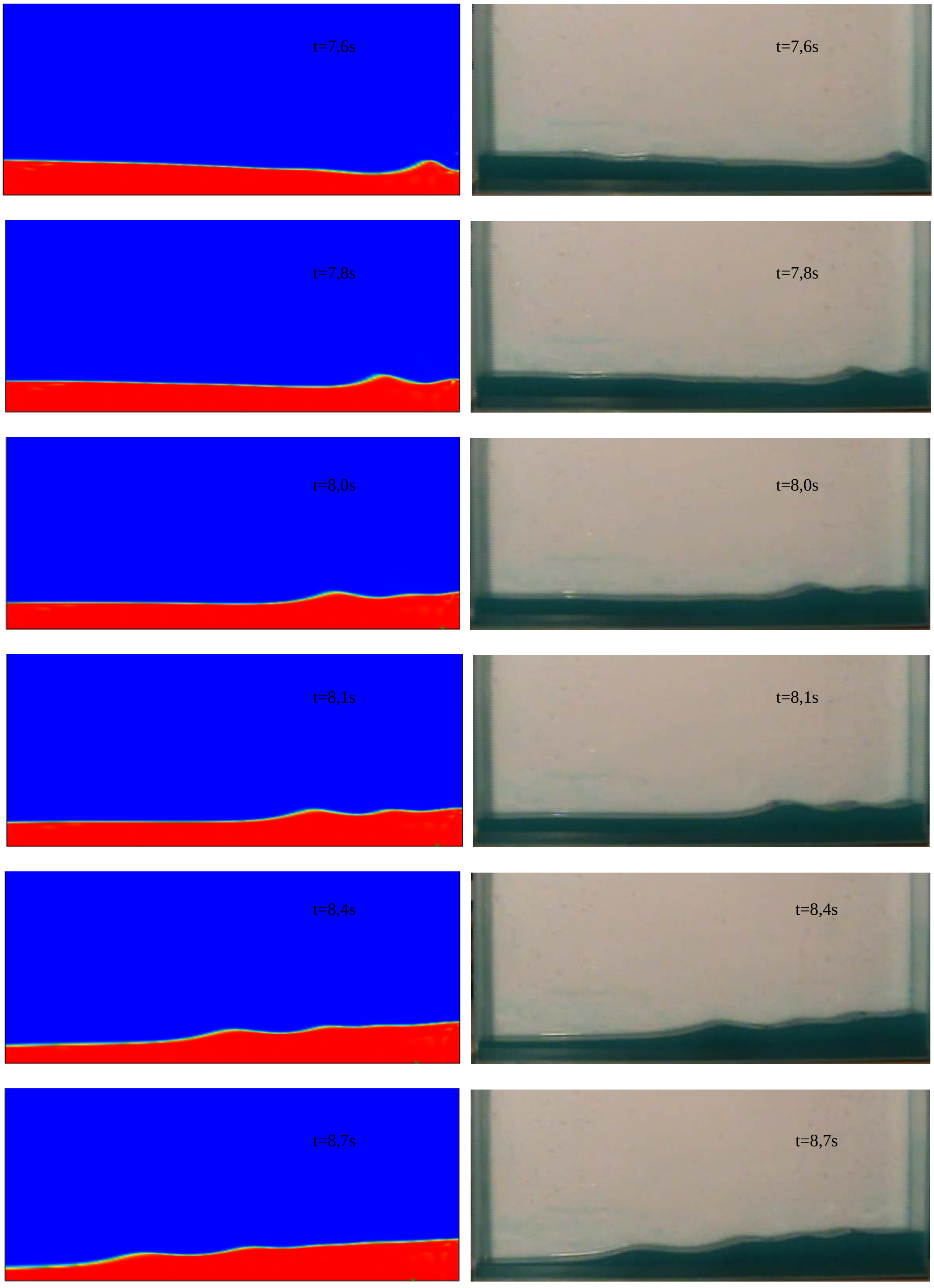


Figure 5. Comparison between numerical (left column) and experimental (right column) free-surface profiles.

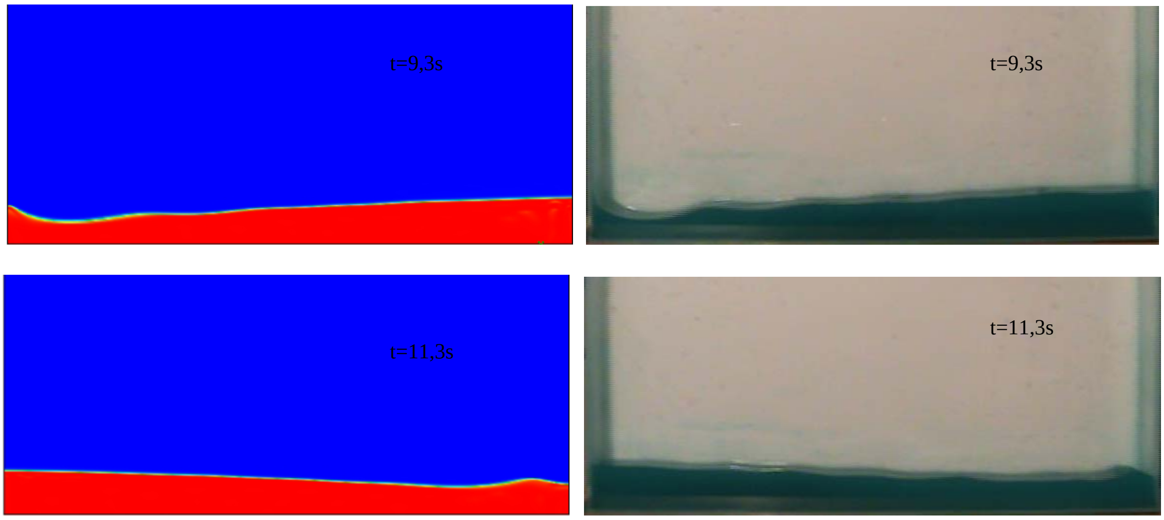


Figure 5 (cont.). Comparison between numerical (left column) and experimental (right column) free-surface profiles.

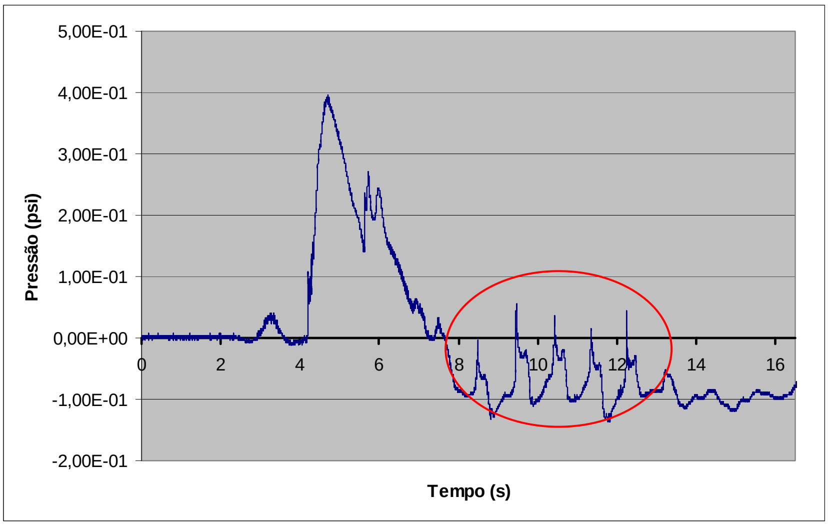


Figure 6. Pressure history from a sensor installed at the N2 tank vertical wall; a manual displacement was imposed. The involved red area indicates a sequence of "church roof" profiles, a common feature observed on sloshing flows.

5. CONCLUSIONS

A shaking table facility was built with the developed hardware and software being able to impose some horizontal displacements to the partially filled reservoir. A good agreement between experimental and numerical results is achieved in both experimental set ups. However, due to limitations of the shaking table mechanism, large wave impacts at the walls could not be reproduced. Preliminary results show that the double peak pressure profile, commonly observed on sloshing flows, can be registered by pressure transducers installed at the vertical walls. As a future work, the shaking table mechanism is going to be reviewed in order to impose higher displacement amplitudes to the reservoir.

6. ACKNOWLEDGEMENTS

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