INVESTIGATION OF ANTI-ROLL TANKS USING A PARTICLE METHOD

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Abstract

In this paper a new technique for the design of passive anti-roll tanks is exposed and validated. The differences with respect to other techniques arise from using the Smoothed Particle Hydrodynamics (SPH) method to perform the simulations. SPH is a particle-meshless method that allows us to model violent free surface deformations and wave breaking, and both phenomena appear in the rolling motion of the water inside the tanks. Real configuration data is compared with numerical data regarding pure quantitative physical magnitudes as moment phase lags with respect to tank movement and more qualitative ones as free surface shapes, for which we present scheduled frames comparisons. Large amplitude waves are well reproduced and the numerical values of phase lags accord fairly well with experiments. Nevertheless, further work must be done in order to improve the accuracy of the method.

1 INTRODUCTION

We present in this paper comparisons of the flow in anti-roll tanks obtained by numerical simulations and experiments. Passive stabilizing tanks are used successfully mainly in fishing vessels to damp their roll motion. This is the reason why they are called roll dampers. A free surface roll-damping tank was first introduced by Philip Watts at the end of the 19th century [30,31]. He described the mechanism by which a roll damping moment was created by the wave action of a fluid in a rectangular tank placed aboard a ship. Frahm in 1911 presented a U-tube form roll damper, but there was a lack of confidence in a device incorporating large quantities of free-moving water, and this type of tanks did not succeed in becoming popular up until the end of the second world war.

These devices have been installed in many countries in the late 40 years, mainly in fishing vessels. Good theoretical work on their behaviour is due to Goodrich *et al*. [9]. It has long been appreciated that a ship rolling in waves can be represented by an equivalent mechanical vibratory system. The mechanical equivalent to an anti-rolling tank is a damped vibration absorber, which can be substituted by other types of liquid tuned absorbers in other types of structures [2,13]. These absorbers, usually rectangular tanks filled with water, are named tuned sloshing dampers (TSD) or tuned liquid dampers (TLD). Many papers have reported on the sloshing phenomena in a rigid rectangular tank. Ikeda *et al*. [13], Modi *et al*. [18], Sun *et al*. [26], Verhagen *et al*. [29] have carried out theoretical and experimental research by means of the shallow water wave theory, Liu *et al*. [15] using finite element method, Celebi *et al*. [7] using VOF method, etc. Extensive comparative study on sloshing loads has been made [6,24].

In this paper, we deal not only with rectangular tanks, but with rectangular tanks with obstacles, see figure 3, in which there are relevant three dimensional effects. We compare with experiments both quantitative magnitudes as the phase lags of the water moment and qualitative aspects as free surface shapes. Tanks with internal obstacles have been investigated by Abad *et al*. [1], Bass *et al*. [4], Weng *et al*. [32] or Armenio *et al*. [3] using experimental tests, but not many studies have been carried out trying to perform numerical simulations. We use here a particular type of gridless method, the SPH method initiated by Lucy in 1977 *et al*. [16]. SPH is a Lagrangian particle method which can be used to simulate a compressible fluid moving arbitrarily in three dimensions [20]. It is robust and simple to program. It was first used in astrophysics [16,20] and its use has already been extended to incompressible fluids with solid boundaries by Monaghan *et al*. [21] and Morris *et al*. [22]. They have modeled the incompressibility by assuming a compressible fluid with a large sound speed, but since results are inadequate in different conditions, other schemes have already been studied by Cummins *et al*. [8].

Although the free surface deformations are severe in many ship hydrodynamics problems, not much work has been done in this field with gridless methods. Tulin *et al*. [27] studied wave breaking problems with splash and the generation of bow breaking waves. For the simulation of the bow breaking waves they have used a mixed particle method-boundary element method approach. Superposing different 2D analysis a 3D approximation is achieved.

Naito *et al*. [23] simulate sloshing problems in large car decks. These sloshing problems are extremely non-linear and complicated. They use MPS (Moving Particle Semi-Implicit) method [14]. The main difference between MPS and SPH is that in MPS the pressure is calculated implicitly by solving a Poisson equation every time step, forcing the divergence free condition to the flow.

In this work we will start by explaining the basics of the stabilizer tanks and their resonant properties; make a review of the basics of the SPH method we use, describe the tests which we have made, and analyze the results, which will have been validated with experimental tests made at the towing tank facilities of the Naval Architecture Department of the Universidad Politécnica de Madrid.

2. THE WATER FLOW IN THE TANK

Tuned liquid dampers are used to reduce the vibration of some structural systems. In this case the structural vibratory system is a ship rolling in waves. The stabilizer tanks are one of the diverse methods that exist to dampen the roll motion of a ship in waves. The dampening effect of the tank is at its maximum when its moment is out of phase 180º with respect to the wave moment so that each tend to cancel the others effect. Because in the worst possible situation (with regard to resonance frequency) the disturbance is out of phase 90º with respect to the motion of the ship, the stabilizer tank is projected in such a way that at this frequency, the disturbance produced by the tank would be out of phase 90º with respect to the motion of the ship thus tending to cancel the other effect.
The tank moment is produced by the shift of the mass of water inside the tank. When a tank containing water is heeled, the water flows to the lowest side. When this heeling is occurring periodically the frequency determines whether the mass of water can keep in phase with the motion.

For very low frequencies the water surface remains of course horizontal, which means that the phase angle between the moment and the motion is zero. The moment amplitude corresponds, in principle, with the well known reduction of stability due to the free fluid surface.

For somewhat larger frequencies the water rises at the sides a little above its position in the statical condition. In general the flow is characterized by a long low standing wave the length of which λ is twice the tank breadth. When we have a rectangular tank with no obstacles, the shallow water dispersion relation lets us calculate the wave velocity [10]. To calculate the main natural frequency of the tank fluid we have to match the wave speed with the tank movement. During one period *T*, the wave has to cover twice the tank breadth *B*, and so the wavelength λ is 2*B*.

With the shallow water wave dispersion relation we obtain the frequency ω of such wave for a depth *h*, *g* being the gravity acceleration:

$$\frac{2\pi}{\lambda}\tanh\frac{2\pi h}{\lambda}=\frac{\omega^2}{g} \quad (1)$$

$$\omega^2=\frac{g\pi}{B}\tanh\frac{\pi h}{B} \quad (2)$$

This gives a first estimate of this value. It is also very interesting to think of the tank as an harmonic oscillator excited by the ship rolling. The first step is to choose the degree of freedom that would characterize this system [28]. The natural election for short amplitude oscillations might be the effective slope of the water in the tank relative to the ship θ. The second step is to define all the coefficients in the harmonic oscillator equation. Although results shown in [9] and [28] are interesting to understand the phenomena, they are not accurate enough for design purposes as this approach can simulate just small amplitude motion with a very limited range of dampening coefficients.

Another option for the degree of freedom consists of substituting the water action with a pendulum held at the tank top. The degree of freedom in this case is the angle of the pendulum relating to the vertical, see [12]. Again this is useful not in general although several corrections may be introduced in the balance equation. These corrections refer to energy dissipation due to collision with the tank walls and interaction with the tank walls pushing the liquid.

When there are relevant three dimensional effects or large free surface deformations the previous models are no longer valid in general because we lack the expressions for all the corrections to introduce in the harmonic equations. Therefore, it is necessary to model the fluid itself with the incompressible non-viscous Navier-Stokes equations, not just the waves as a distinct thing. To discretize and integrate these equations we use the SPH method.

3. SPH METHOD

In SPH the fluid is represented by a set of particles which follow the fluid motion and advect fluid quantities such as mass and moment [8]. Associated with particle *j* is its position $\mathbf{r}_j$, velocity $\mathbf{v}_j$, and mass m_j. In addition, each particle carries SPH-specific parameters including a purely numerical "smoothing length" h_i, specifying the local spatial resolution, that we will suppose constant [21]. Smoothness and differentiability of functions are achieved using an interpolation kernel *W* and summations over the particles.
If we consider that a function $f(\mathbf{r})$ is known on a set of *N* distributed points $\mathbf{r}_j$, we can approximate its value by:

$$\langle f(r)\rangle=\sum_{j=1}^{N}\frac{m_j}{\rho_j}f(r_j)W(r-r_j,h_j) \quad (3)$$

ρ_j being the volumetric density, which can be estimated from this formula as:

$$\rho_i = \sum_{j=1}^{N} m_j . W(r_i - r_j, h) \qquad (4)$$

For the interpolation kernel we use the spline form of Monaghan *et al*. [19] which has a compact support, see figure 1, and reduces the extension of the sums to those neighbors within this support.

$$W(r,h) = \frac{1}{\pi h^3} \begin{cases} 1 - \frac{3}{2}\left(\frac{r}{h}\right)^2 + \frac{3}{4}\left(\frac{r}{h}\right)^3 & 0 \le (\frac{r}{h}) < 1 \\ \frac{1}{4}\left(\frac{2-r}{h}\right)^3 & 1 \le (\frac{r}{h}) < 2 \\ 0 & (\frac{r}{h}) \ge 2 \end{cases} \qquad (5)$$

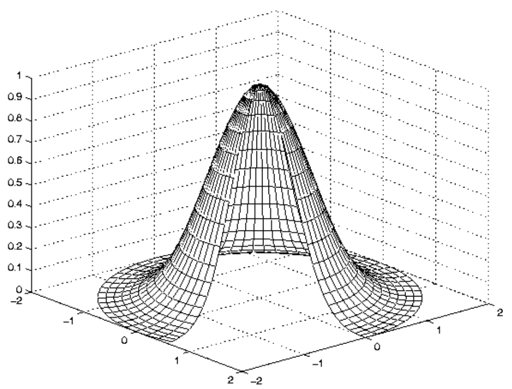

Figure 1: Sketch of the
kernel function in two dimensions

3.1 SPH modelling of Navier-Stokes equations

The interpolation scheme in equation 3 can be applied to the equations of the fluid mechanics to get the continuity, moment, and state equations for each fluid particle [17]. There are a number of ways in which the Navier-Stokes equations can be represented in SPH . The formulation implemented here is described by Monaghan *et al*. [20], and represents the moment equation at a particle *i* as

$$\frac{dv_i}{dt} = \sum_{j=1}^{N} m_j \left(\frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2}\right) \nabla W_{ij} + g \qquad (6)$$

Where:
P_i pressure in particle *i*.
W_{ij} represents $W(r_i\text{-}r_j,h)$.
g gravity.
$\mathbf{v}_i$ speed of particle *i*.

The equation of continuity is as follows.

$$\frac{d\rho_i}{dt} = \sum_{j=1}^{N} m_j (v_i - v_j) \nabla W_{ij} \qquad (7)$$

It is important to notice that the incompressibility of liquids is not imposed in the continuity equation. The explanation is that SPH method was first conceived for gas simulation. In order to solve the problem of the method being applicable only to compressible fluids, we modify the state equation to obtain density variations of an order of magnitude so that in practice, the fluid is incompressible [21]. Therefore pressure is obtained with the state equation from density. To calculate density, equations 4 or 7 may be used but as mass conservation is inherent to this type of system we use 4. There are other ways to enforce incompressibility , see Cummins *et al.* [8] and Koshizuka *et al*. [14], which we have not implemented yet. Besides, although the problem is basically non-viscous, we keep the viscosity factor as we have found that a small dissipation stabilizes the time integration process. To understand the viscosity correction, let us write the one dimensional momentum equation with viscosity:

$$\frac{dv}{dt} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{1}{\rho}\frac{\partial}{\partial x}(\mu \frac{\partial v}{\partial x}) \qquad (8)$$

that can be rewritten as,

$$\frac{dv}{dt} = -\frac{1}{\rho}\frac{\partial}{\partial x}(P - \mu\frac{\partial v}{\partial x}) \qquad (9)$$

It is clear from 9 that the viscosity term is acting as an artificial pressure term. When particles are moving together ($\partial v/\partial x < 0$), from the continuity equation, we can say that the density is increasing. In this case, the artificial pressure also increases to resist the density increase. Using this idea a symmetric viscosity term Π_{ij} is added to equation 6 such that,

$$\Pi_{ij} \approx \frac{\mu}{\rho^2}\frac{\partial v}{\partial x} \qquad (10)$$

leading to a suitable SPH viscosity term,

$$\Pi_{ij} \approx \alpha h \frac{c}{\rho_{ij}} \frac{v_{ij} r_{ij}}{r_{ij}^2 + \eta^2} \qquad (11)$$

Artificial viscosity was introduced into SPH gas dynamics problems to stabilize the calculations by limiting the motions of particles which are moving together. The flows we are computing are fast moving and often turbulent and therefore viscous layers do not form. Morris *et al*. [22] introduced a realistic viscous term in their low Reynolds number computations. This is not advisable in our calculations since we try to reproduce a phenomenon which is actually scalable with the Froude number, therefore for which viscosity scale effects are assumed neglectful.

3.2 Neighbors search

Although the SPH algorithm does not require the use of a grid for computing derivatives, having a reference one helps a lot in reducing the number of operations in the summations. The kernel reduced support allows us to extend the summations only to those particles within a distance $2h$ of each other. Linked Lists [11] are an efficient way of determining which particles are within the smoothing length.

The idea is to place a grid of cubes (with sides of length $2h$) around the particles in the simulation. Each cell then has a pointer (Head of Chain) that gives either the identifying number for the first particle in the cell, or zero if the cell contains no particles. The first particle in the cell then contains a pointer (link) to the second particle in the cell and so forth.
At the start of each time step, the grid is constructed and the Head of Chain array is initialised to zero. Each particle is tested to see in which cube it belongs. The particle is then placed at the Head Of Chain for that cube with its link pointing to the previous particle at the Head Of Chain. When we wish to find the particles required for summations we transverse each cube and treat it as the *homecube*. We examine particles in the *homecube* with all the particles in the neighboring 27 cubes, and include them in the summations if they are within the $2h$ smoothing distance. However we only need to include half the neighboring cubes if we make use of the symmetry of the interactions between particles.

3.3 Time integration

We employ a first-order Euler scheme. The particle positions are advected with the particle velocities, and the velocities with the particle accelerations obtained from equation (6):

$$r_i^{k+1} = r_i^k + \Delta t v^k \qquad (12)$$

$$v_i^{k+1} = v_i^k + \Delta t(\frac{dv_i}{dt})^k \qquad (13)$$

We use this first order scheme because it makes it easier to control the collisions with the tank walls. The collision time partially defines the time step and with an Euler scheme it is simple to reduce the time step in order not to collide with the boundaries. Since the time steps required for the collision criteria are very small, it is not worth having a higher order integration scheme. The other criteria defining the time step is that we have the stability condition [20], and a limit given by the value *h* which says that the time step will be set in such a way that during this time step the distance covered by a particle will not be higher than *h*/10, *h* being the smoothing length. In our implementation we use the same time step for all particles and we choose it as the minimum obtained by the three exposed criteria. The calculation times are rather high, and we are trying to improve that. Every test takes around 3 hours in a Pentium 3 GHz for around $5 \cdot 10^4$ particles.

3.4 Boundary conditions

Due to simplicity and computational efficiency of the method the boundary conditions implementation is again basic. We assume that the interaction of every particle with the tank walls consists of an inelastic collision whose parameters can be defined. In this case, no dissipation was considered in these collisions since the boundary layer is very thin.

This treatment leads to certain inaccuracies that we are trying to overcome following several techniques described in [5], [21] and [22].

4. EXPERIMENTAL AND SIMULATION METHODOLOGIES

4.1 Experimental tests and validation

The test device consists of a mechanical part used to move the tank periodically changing amplitudes and frequencies. It also consists of an electronic system aimed at registering the signals generated by the tank water.

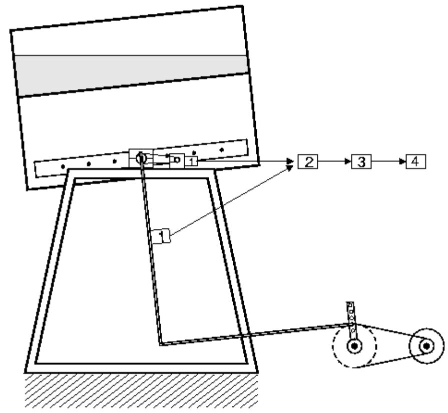

Figure 2: Sketch of the experimental device. 1 Gauges, 2 Data acquisition system, 3 Filtering and 4 Analysis

The movement of the tank is registered with a potentiometer, and the rolling moment with a system of extensometric gauges. These devices transform linearly the magnitudes: oscillation angle and rolling axis moment in electric tensions (mV), that amplified, are registered with the computer. The obtained moment signal is filtered to get the response to the considered disturbance frequency. This signal is characterized then by an amplitude and by a phase lag with respect to the disturbance signal. The goal is designing the tank in a way that the maximum amplitude corresponds to a phase lag of approximately 90º, to get the maximum counter moment, see figure 2.

A display has been also installed showing the position of the tank in its periodic movement. We record the movement and the display with a digital video camera. With this technique, we are able to extract and schedule every single frame of the water flow inside the tank. We present in next sections extensive comparisons with the predictions.

For the validation of the described method a number of cases were prepared based on the experimental work developed at the towing tank. In this paper, we will concentrate in a rectangular stabilizer tank used by a cablelaying vessel. Although several inner configurations for the projected stabilizer tank had been tried, we have focused just on two of them: the simplest, without any baffles and therefore without relevant three dimensional effects, and another with baffles. The tank has a rectangular section 14.0 cm deep shown in figure 3.

In this figure it is also possible to see the position of the baffles in the case when it has them. Its down face is 27.2 cm over the rolling axis (assumed as the gravity center) at the load condition we tested. This is a very important detail as the distance is large and therefore the motion inside the tank is very violent, even for low frequencies. For this study, three different filling levels have been tested: 3.0 cm, 4.0 cm and 5.0 cm as well as two different roll amplitudes (3º and 6º) and of course different frequencies of oscillation.

We use in the experiments and in the simulation a length scale λ = 25. As a consequence, the unit of time is divided by $\sqrt{\lambda}$ = 5. Thus, the values of the typical ship's resonance periods that we want to focus on are changed from 9 – 11 sec in the real scale to 1.8 - 2.2 sec in the model scale.

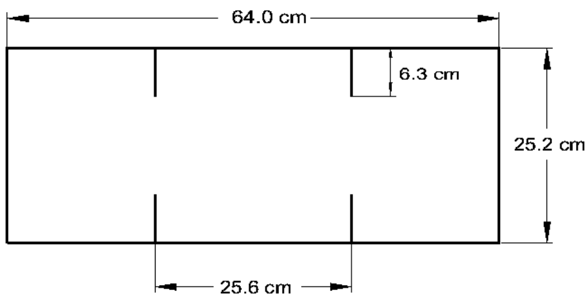

Figure 3: Rectangular tank with baffles ground section.

4.2 Simulation methodology

Our simulation process can be divided in three phases: preprocess, process and postprocess. In the phase of preprocess the stabilizer tank is modelled and then animated with movement in agreement with the roll frequency to which the test is made. For this, it is possible to use 3D modelling and animation programs or specific applications designed for this purpose. This is a very powerful approach since very complicated animated motions can be reproduced and subsequent flows calculated. Once the animated sequence has been generated, calculations are performed with the SPH code, Real Flow©, by Next Limit, with whom we have been collaborating in theoretical aspects and validation of the code. As a result, speed and pressure of all particles involved in the animation are known for every instant of time. In the phase of post-process the stabilizer moment generated by the tank is obtained and it is compared with the experimental results. Since the program offers the position and speed of particles, the moment of momentum is calculated with respect to the origin for the particle system. We apply a Fourier filter to the obtained moment curve. We extract the component of equal frequency to the frequency of oscillation of the tank, and take the derivative of this component to obtain the angular moment (the moment of the accelerations of the particles). In order to avoid transitory signal, which takes place when starting the tank, the filtering is applied only to the final part of the obtained signal, ignoring approximately two periods at the beginning. The signal has relevant higher frequency components, but with less energy than the main one. The same happens in the experimental register. We add to this moment the weight moment of the particles, again with respect to the origin of the particle system, taken always as the rolling axis.

This register is again filtered. Contrary to what happens with the moment of momentum, here there is just one relevant harmonic in the signal, the one corresponding to the disturbance. It would be good to have the chance to obtain experimentally both components.

5. RESULTS COMPARISON

We present two types of results. The first type is purely quantitative and corresponds to the phase lags of the first harmonic component of the moment response. We seek the configuration and water level which is out of phase 90º for the structure resonant condition (ship's natural frequency). We have not compared amplitudes so far. The second type is qualitative and very interesting and corresponds to the shape of the free surface with the aim of comparing experimental with numerical predictions for the whole series of scheduled frames in the motion.

5.1 Phase lags

Rectangular tank without baffles

For the rectangular tank without baffles, the results demonstrate good agreement for a wide range of frequencies including the zone close to the ship's resonance period (1.8 - 2.2 s in the model scale). Figures 4 to 9 present results for the 3 different filling levels and the 2 different amplitudes of the rolling motion. We can notice that the agreement between experimentations and simulations is poorer for the maximum filling level (5.0 cm), where the phase lags are higher in the simulation. But in all this cases, we need to impose a disturbance period of around 1.6 seconds to get a phase lag of 90º. This period is lower than the resonance one. Therefore, this configuration is rejected.

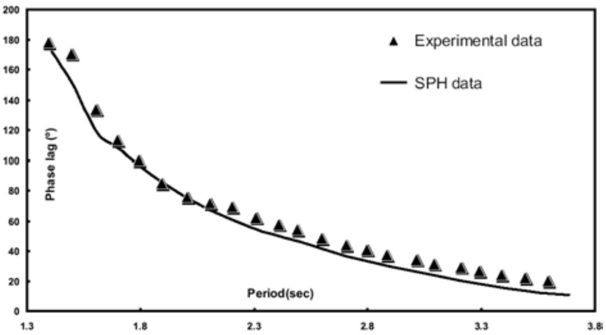

Figure 4: Phase lag, rectangular tank without baffles, water level 3.0 cm., amplitude of the roll motion 3 deg

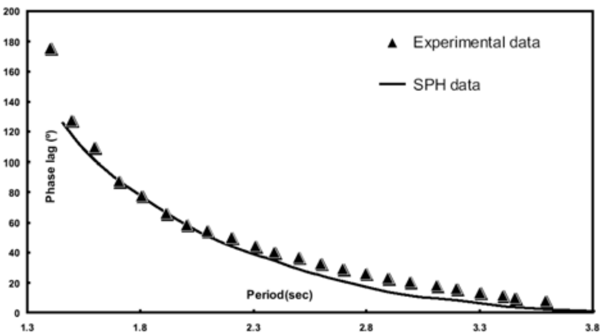

Figure 5: Phase lag, rectangular tank without baffles, water level 4.0 cm., amplitude of the roll motion 3 deg

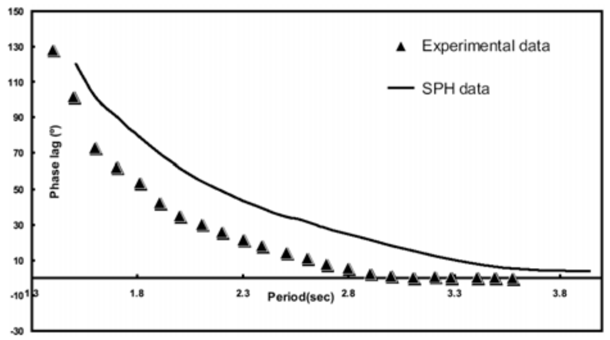

Figure 6: Phase lag, rectangular tank without baffles, water level 5.0 cm., amplitude of the roll motion 3 deg

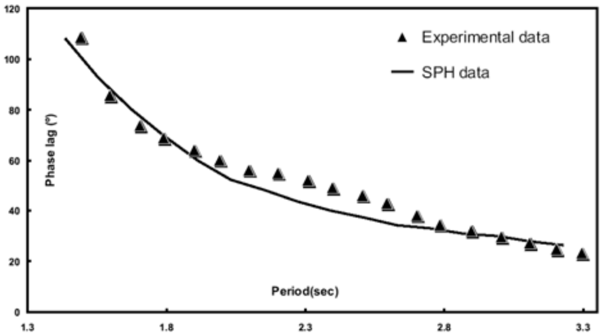

Figure 7: Phase lag, rectangular tank without baffles, water level 3.0 cm., amplitude of the roll motion 6 deg

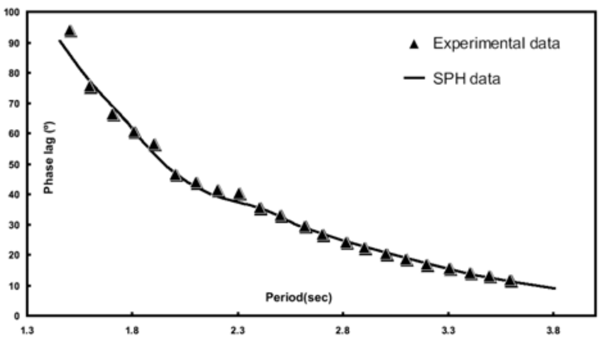

Figure 8: Phase lag, rectangular tank without baffles, water level 4.0 cm., amplitude of the roll motion 6 deg

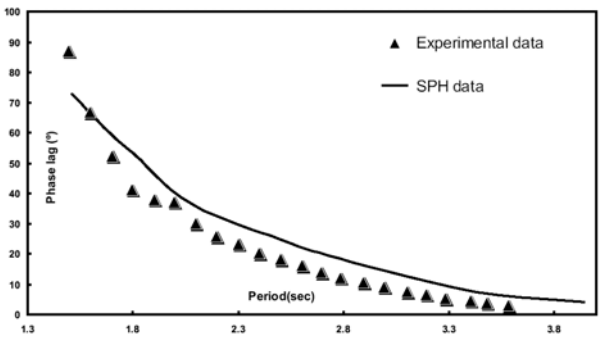

Figure 9: Phase lag, rectangular tank without baffles, water level 5.0 cm., amplitude of the roll motion 6 deg

Rectangular tank with baffles

We have also tried the configuration with baffles, where the numerical overall tendency is very similar to the experimental one, as we can see in figures 10 to 15. The agreement is poorer for low periods -under 1.5 seconds in the model scale- for the maximum filling level, 5.0 cm. In figure 13, experimental variations in the tendencies around the frequency 1.8 seconds can be observed and are not well predicted by the simulation. The 90º phase lag was not achieved and so this configuration was also rejected.

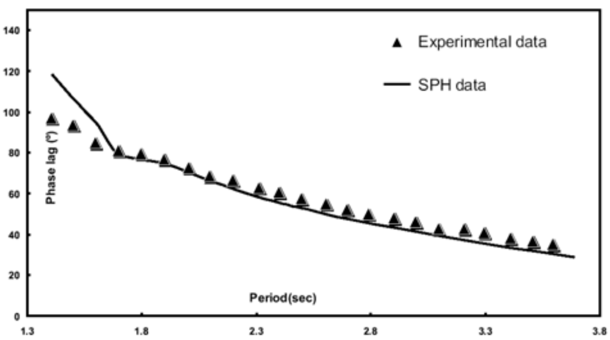

Figure 10: Phase lag, rectangular tank with baffles, water level 3.0 cm., amplitude of the roll motion 3 deg

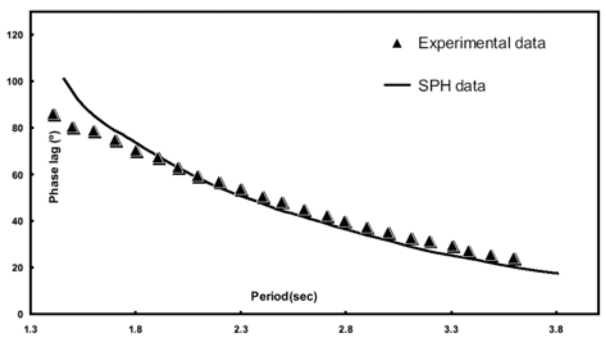

Figure11: Phase lag, rectangular tank with baffles, water level 4.0 cm., amplitude of the roll motion 3 deg

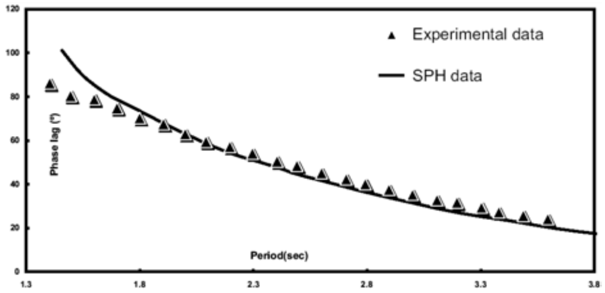

Figure 12: Phase lag, rectangular tank with baffles, water level 5.0 cm., amplitude of the roll motion 3 deg

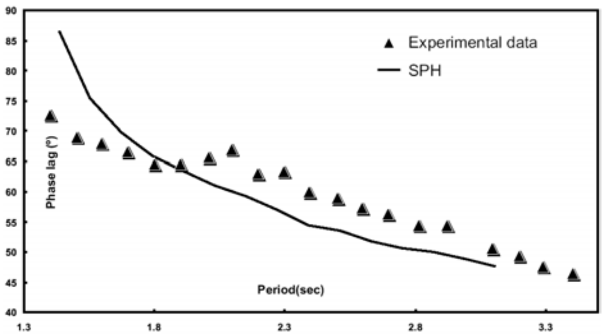

Figure 13: Phase lag, rectangular tank with baffles, water level 3.0 cm., amplitude of the roll motion 6 deg

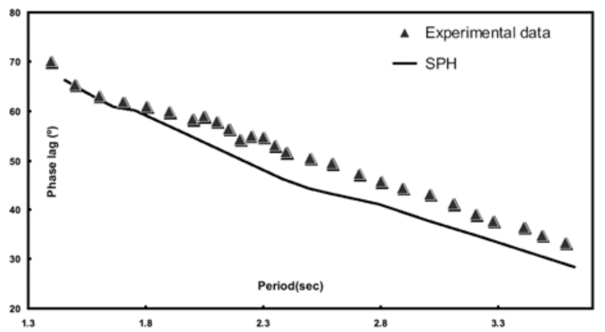

Figure 14: Phase lag, rectangular tank with baffles, water level 4.0 cm., amplitude of the roll motion 6 deg

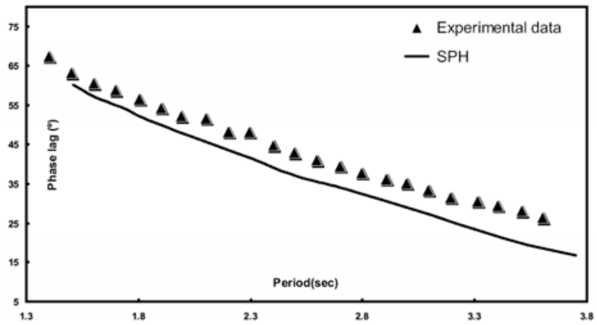

Figure 15: Phase lag, rectangular tank with baffles, water level 5.0 cm., amplitude of the roll motion 6 deg

More details about these configurations, in addition with investigations on a C tank configuration can be found [25].

5.2 Free surface shape

The behavior of the free surface and of the whole fluid in the tank are presented here and the visualizations obtained by SPH simulations are compared with these obtained by the experiments. The most interesting free surface shapes occur when the rolling axis is far away from the tank. In these cases the motion can be very violent, even for low frequencies. The tank we have tested with and without baffles, see figure 3, falls into this type. It is 14 cm deep and 64 cm broad, and the distance of its bottom side to the rolling axis is 27.2 cm. Therefore its gravity center is far from the rolling axis.

Rectangular tank without baffles

We present images for a case in which the rolling amplitude is 6º, the filling level is 4.0 cm. and the period is 1.59 sec. We show frames for half a complete period in the figure 18. It is possible to see that the breaking wave is quite well approximated by the simulation. Nevertheless it is accepted that there is a certain lack of disturbance in the water motion that needs further investigation. Apart from this, it is possible to see that there is a small lag in the motion with respect to the experimental results that requires further investigation.

Rectangular tank with baffles

Again, the rolling amplitude is 6º, the filling level is 4.0 cm. and the period is 1.59 sec and we present as well results for half a complete period in the figure 19. No breaking waves appear and the free surface shapes are fairly well reproduced. Again a certain lack of disturbance in the water motion is observed probably related with the artificial viscosity, but there is no lag between the simulations and the experimental images.

We also present for this case a top view of the particles motion and a perspective view, see figure 16 and 17, in order to show the three dimensional effects that appear when the baffles are added. The figure 17 is a frame of an animation of the fluid motion in the tank built from the position of the particles during the simulations.

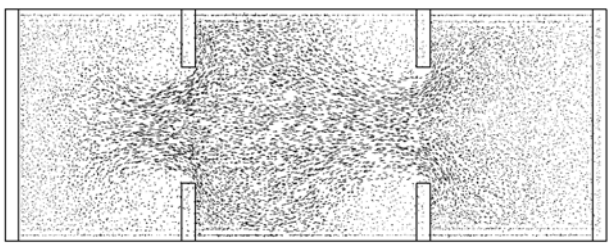

Figure 16: Rectangular tank with baffles. Maximum amplitude, top view.
Simulation

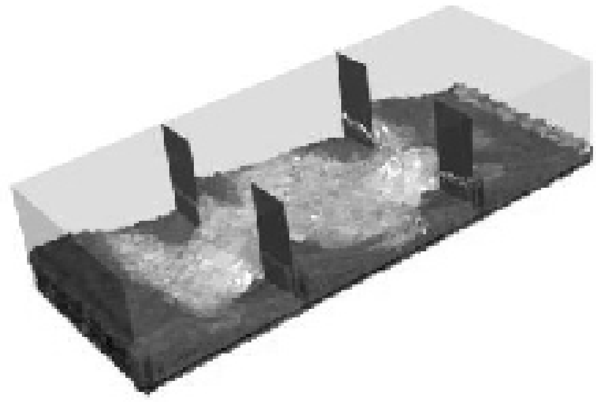

Figure 17: picture extracted from the 3D animation of the flow in the tank. The water level is 4 cm., the amplitude of the roll motion 6 deg. and the period of excitation is 1.6 sec

5. CONCLUSIONS AND FUTURE WORK

We have used a novel particle-meshless method, SPH, to model and simulate the water flow inside anti-roll tanks. We have presented results corresponding to the analysis of the moment generated by the water inside the tank and a scheduled comparison between the free surface shapes in both numerical and experimental cases. For the study cases presented here, quantitative results are promising and the free surface shapes accord with the experimental ones in the most damped cases. Nevertheless, certain lack of accuracy in the phase lags leads to a moderate delay between the numerical shapes and the experimental ones for the most violent free surface motion. Therefore, further investigation has to be done. This investigation will take into account effects caused by the artificial viscosity factor, the incompressibility condition and the treatment of the boundary conditions. Apart from this type of calculation, we are working in multi phase flows with SPH with the aim of simulating damage stability problems. In these problems, the presence of air in the holds affects the dynamics of the incoming water much more than one could expect. In this sense it is necessary to integrate the equations not only for the denser fluid, water, but also for the lighter one, the air.

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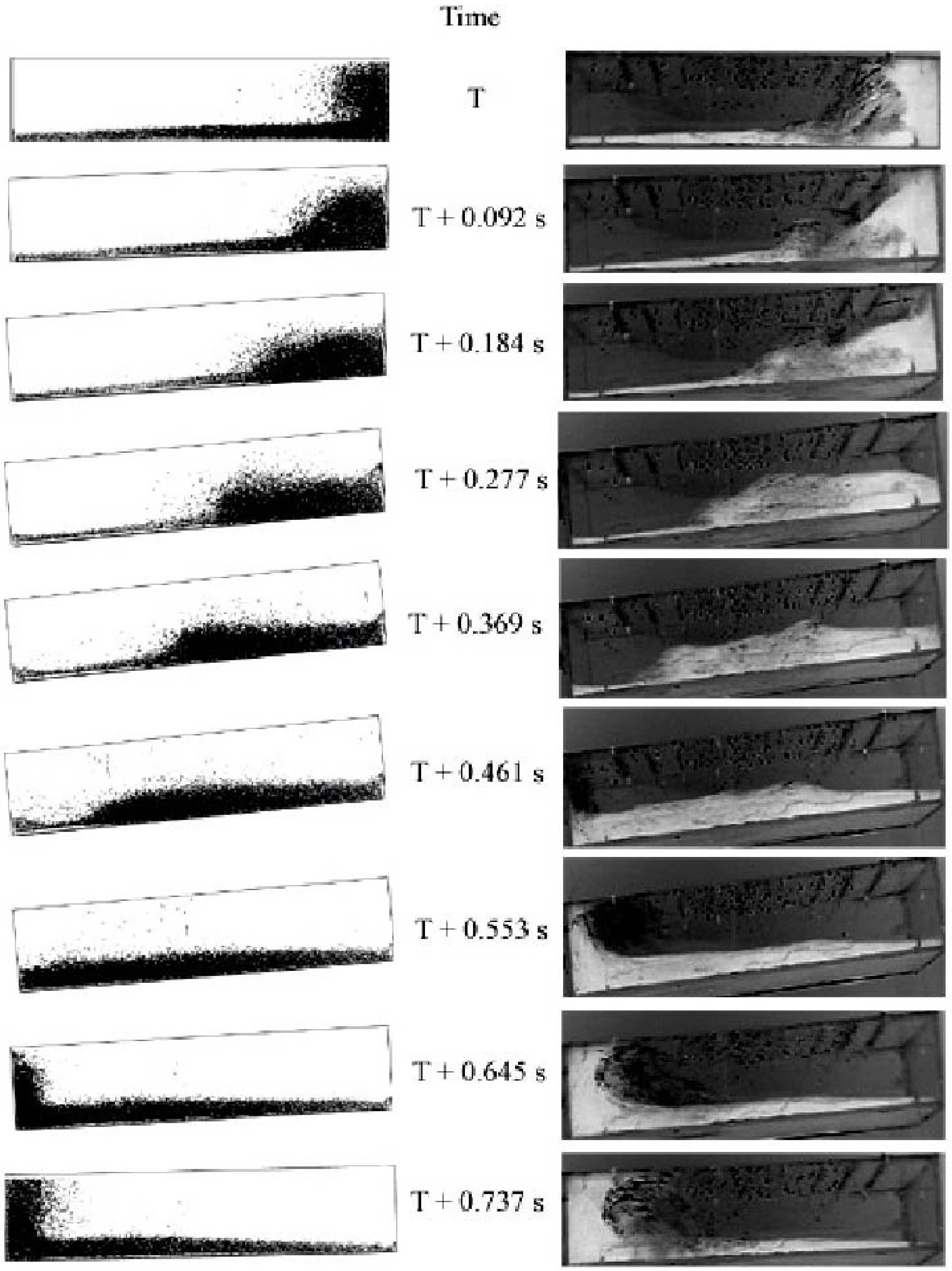

Figure 18: Comparisons
between simulation and experiment. Rectangular tank without baffles. The water level is 4 cm., the amplitude of the roll motion is 6 deg. and the period of excitation is 1.6 sec.

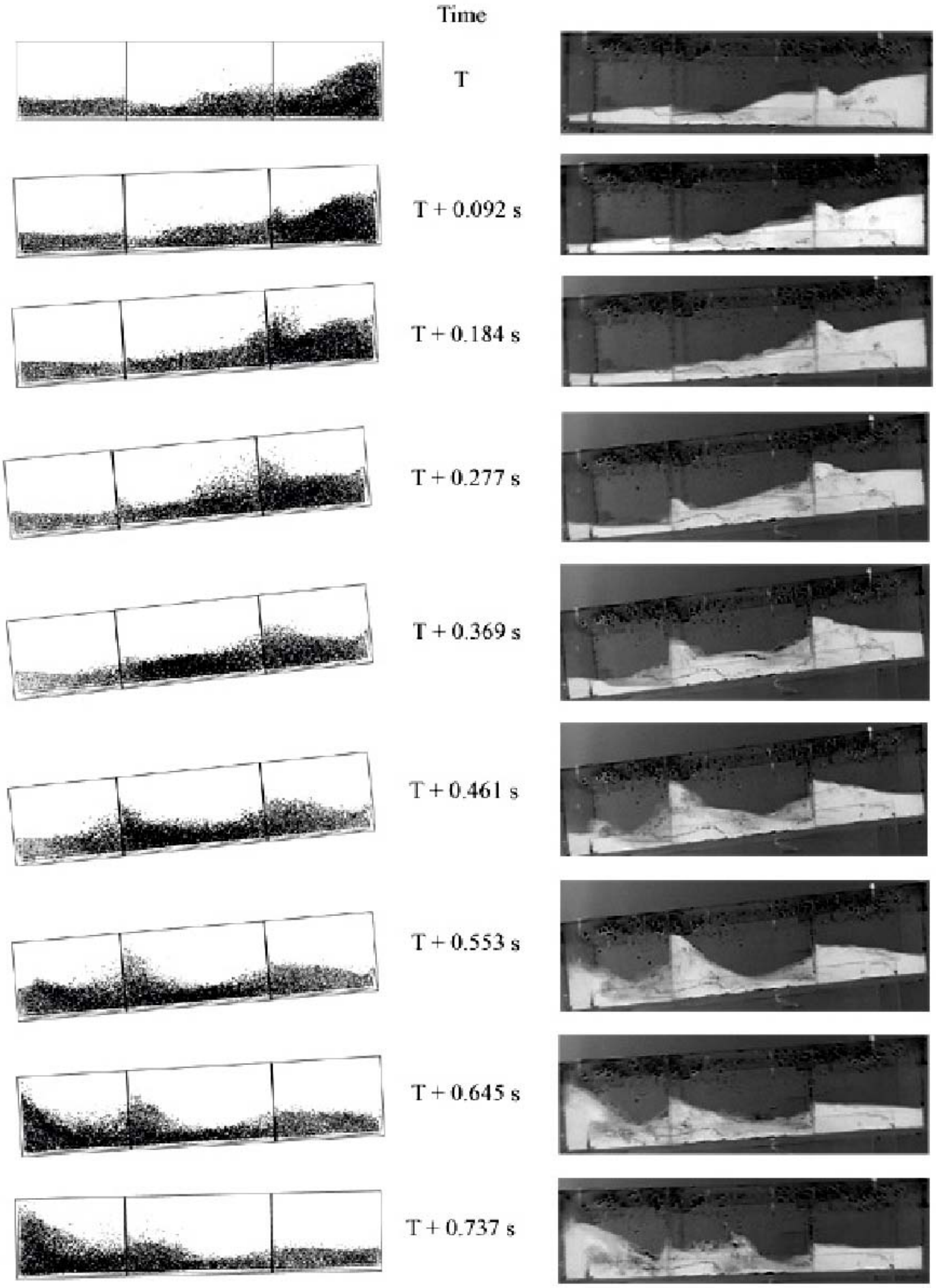

Figure 19: Comparisons
between simulation and experiment. Rectangular tank with baffles.
The water level is 4 cm., the amplitude of the roll motion is 6
deg. and the period of excitation is 1.6 sec.