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Experimental and numerical investigation of sloshing in anti-roll tank using effective gravity angle

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1) Introduction

Anti-roll tanks (ART) are commonly used by naval architects to deal with the lightly damped roll motion. As well as improving the roll behavior even at low or zero speed, they offer the advantage of simplicity, low cost and no extra added resistance. The investigation carried out in the present research takes part in the design and optimization of a new concept of passive anti-roll tank driven by non-linear free-surface flow phenomena and bathtub vortex (figure 1). In addition to harnessing the roll stabilizing moment from the sloshing of liquid, the kinetic energy of the vortex can be harvested using water turbines providing a new source of energy on board. The bathtub vortex (figure 2) have been studied both experimentally and numerically by Fourestier [1, 2]. Here, the focus is on the experimental and numerical modelling of the free-surface flow to properly account for the effect of sloshing in the ship global response.

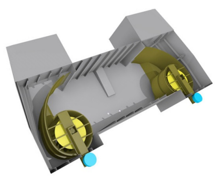

FIGURE 1 – GSIRE® type passive anti-roll stabilization system developed by GEPS Techno

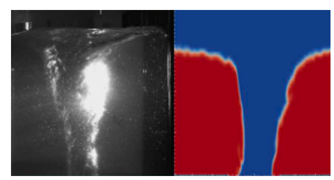

FIGURE 2 – Experimental and numerical bathtub vortex

In a linear seakeeping approach, both ship and tank hydrodynamic coefficients are calculated by the potential flow theory. Since the response of the tank may be strongly non-linear, solving the sloshing problem using the linear potential theory may be unsuitable even with a tuned artificial damping. Alternatively, the dynamic coupling between liquid motions in tank and seakeeping of the floating body can be assessed by a hybrid model [3, 4, 5]. Whereas the external flow around the ship hull is solved with a 3D panel method based on the linear potential flow theory, the inner tank liquid motions are evaluated with the two-phase incompressible Reynolds Averaged Navier-Stokes (RANS) equations and a Volume Of Fluid (VOF) technique. Here, the potential code HydroSTAR [1] is used for the hull hydrodynamics and the open source CFD development platform OpenFOAM for the tank sloshing (InterDyMFoam solver is used). Since ART response is mainly driven by sway and roll, the hydrodynamic coefficients related to these degrees of freedom are necessary. With OpenFOAM, the tank is numerically forced in pure sinusoidal roll motion for varying periods from 5 to 18 s and amplitudes from 1 to 10 deg. Alternatively, the tank is forced in pure sinusoidal sway motion for the same periods and for the amplitudes $T_y = (0.5, 1, 2)$m. For each simulation, the force and moment acting on the tank are linearly approximated to calculate the added mass and the damping coefficients. For each couple (T_y, R_x), the RAO of the ship is then calculated by coupling the hydrodynamic coefficients of tank from CFD with the hull hydrodynamics [6]. This hybrid approach is applied to the case of the oceanographic vessel of Ifremer, Thalassa, integrating this new concept of ART. Figure 3 depicts the comparison between experimental measurement and results from this hybrid approach. The roll response corresponding to different forcing amplitudes is plotted. The couple (T_y, R_x) are calibrated with regard to experimental tests conducted in the wave basin of Ifremer (Brest, France). Here $(T_y, R_x) = (0.5\text{m}, 4\text{deg})$ and $(0.5\text{m}, 6\text{deg})$ give good agreement with model tests results.

1. The state-of-the-art hydrodynamic software developed by Bureau Veritas

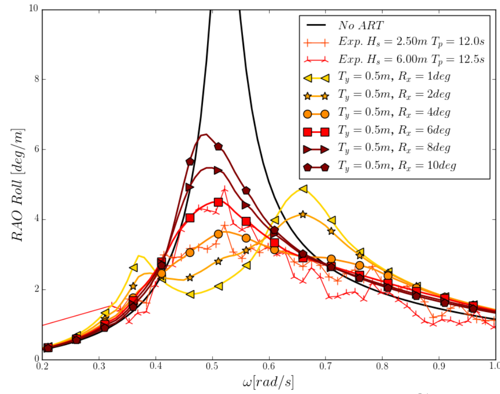

FIGURE 3 – Roll response for the oceanographic vessel Thalassa. Comparison between experimental tests at scale 1 :25 (thin lines) and hybrid (potential + CFD) simulation for different roll amplitudes (Sway is hold at 0.5m) (bold lines)

2) Concept of effective gravity angle

In practice the use of the presented hybrid approach is limited since it requires a calibration of (T_y, R_x) with experimental data. Diebold et al. [5] tackle this drawback using the Effective Gravity Angle (EGA). In fact, the EGA can be used as a unique forcing amplitude instead of the pair (Ty, Rx). The concept of EGA was recently introduced by Carette [7] for the study of ART excited in sway motion. The tank-fixed coordinate system is described figure 4. The EGA is the angle whose tangent is the ratio between the tank-fixed lateral $\ddot{y}$ and vertical $\ddot{z}$ accelerations. Both accelerations include the contribution of gravity. It reads :

$$EGA = \arctan\left(\frac{\ddot{y}}{\ddot{z}}\right) \tag{1}$$

It can be further developed in the case of a combined ordinary sway/roll motion $Ty(t)/Rx(t)$:

$$EGA(t) = \arctan\left(\frac{\ddot{T}_y(t) - \Delta\ddot{R}_x(t) + g\sin\left(R_x(t)\right)}{-\Delta\dot{R}_x^2(t) + g\cos(R_x(t))}\right) \tag{2}$$

Where the dots denote first and second time derivatives. Δ is the distance along z-axis in the tank-fixed frame between the rotation point and the center of mass of the liquid and g is the acceleration due to gravity. Assuming small angles, the EGA for pure sinusoidal sway motion (of amplitude T_y) and pure sinusoidal roll motion (of amplitude R_x) of circular frequency ω can be derived :

$$EGA_{sway} = \arctan\left(-\omega^2 T_y/g\right) \qquad\qquad EGA_{roll} = R_x \tag{3}$$

In [5, 7], it is shown that the hydrodynamic response force F_y and moment M_x are very comparable for different motions with the same EGA. Both pure sway, pure roll or combined sway/heave/roll motions were considered either in regular and irregular conditions. It results that the flow dynamics can be treated indifferently for pure sway, pure roll or combined sway/heave/roll motions with the same EGA. The response of ART is then driven by the unique quantity EGA. In [5, 7], this conclusion has been drawn in the scope of rectangular ART with small appendages for various water filling ratios.

The present work extends the validation made in [5, 6]. It aims at showing that the EGA can be used for any ART devices even with large appendages which can strongly disturb the flow. On the basis of experiments with forced motions, the concept of EGA is validated for different appendage configurations. The new design of passive anti-roll tank integrating bathtub vortices is tested. Not only the force and moment but also the free surface elevation are compared for different types of motions but provided that their respective EGA are similar. The following sections focus on the experimental setup and illustrative results are shown.

3) Test setup

The experimental campaign intends to test different tank configurations. Then we expect to validate the concept of EGA for each of them. The tests are carried out on a Hexapod in the facilities of Ifremer (Brest, France). The rectangular tank without any appendages is the first tested configuration. It is used as a reference case for the others configurations where appendages are added. The tank is made of aluminum except the front face which is made of PMMA. The tank size is $L = 1.5$m long and $B = 0.25$m wide. The roof is set at two vertical positions $H = (0.3, 0.5)$m. The time and space variation of the ullage pressure is not of concern in the present work but could be studied in future works. Three filling ratios are considered $h/L = (0.06, 0.08, 0.1)$m. Different configurations of tank are tested successively :

- Rectangular tank without appendages,
- Rectangular tank with one pair of stiffeners located at the mid-tank ($y = 0$) and obstructing 25% of the width,
- Rectangular tank with three pairs of stiffeners evenly spaced and obstructing 25% of the width,
- ART with bathtub vortex developed by GEPS Techno (at scale of 1 :10). It consists of the rectangular tank with specific internal members at the extreme parts of the tank. The area where sloshing occurs is reduced and two bathtub vortices appear. The first natural sloshing frequency of tank ($f_1 = (g\pi/L \tanh(\pi h/L))^{1/2}$) is then modified due to a shorter tank,
- From the previous case, three other configurations are created by slight modifications of the appendages.

The Hexapod system (SYMETRIE MISTRAL800) forces the tank with various type of excitation (figure 4). Different vertical positions of the rotation point are considered. First, the response to pure sway and roll sinusoidal motions are tested respectively with an amplitude of $T_y = (0.025, 0.05, 0.1, 0.2)$m and $R_x = (0.5, 1, 2, 5, 10)$deg. A series of 15 frequencies ranged between $0.34 < f/f_1 < 1.66$ and discretized more accurately around the first natural frequency of the tank are tested. The different free surface patterns described in [8] are observed : for low frequency excitation a standing wave is generated, for higher frequencies a train wave appears then an hydraulic jump travels from one side of the tank to the other. In the end, a solitary wave appears (figure 5). Combined sway/roll and roll/heave are considered with different prescribed phase lags. These 1D and 2D motions are also performed during 300 s irregular tests based on JONSWAP and pink noise types spectra. Finally real 3DOF (sway/roll/heave) and 6DOF irregular ship motions are used. For that purpose experimental campaigns made with GEPS Techno's systems in the wave basin of Ifremer are used. During the tests, the global force/moment acting on the tank are recorded using a force/torque sensor (MC12 1000 by AMTI). The sensor is placed between the tank and the Hexapod. It measures the force and moment in the three directions. The tank is equipped with eight capacitive wave probes located vertically at $y/L = (-0.475, -0.205, -0.125, 0.000, 0.125, 0.250, 0.375, 0.475)$. The point $y = 0$m corresponds to the center of the tank. A digital video camera records the flow with a sampling frequency of 30 fps and a spatial resolution 1920x1080. Experiments are carried out in a dark room where only the tank is enlightened with a LED ruler surrounding the tank as in figure 4. Fluorescein is used to improve the detection of the free surface.

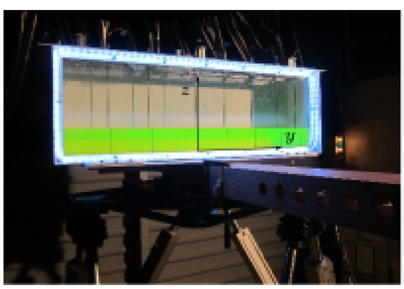

FIGURE 4 – Experimental set-up. Tank mounted on the Hexapod

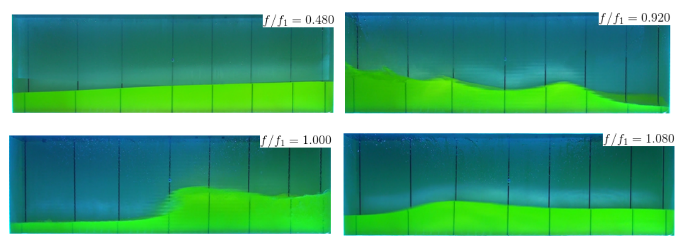

FIGURE 5 – Free surface shapes for shallow-water roll excitation. Standing wave, train wave, hydraulic jump and solitary wave.

4) Some illustrative results

Motions with the same EGA are run. First, pure sinusoidal sway and pure sinusoidal roll motions with the same EGA are compared for the full ranges of frequencies and amplitudes. More complex motions with the same EGA are also tested. Irregular sway motions, irregular roll motions and irregular 3DOF (sway/heave/roll) and 6DOF with the same EGA are simulated. Some of the tank configurations listed above are considered. What is remarkable is that both the free surface elevations, the force F_y and the moment M_x are very similar for motions with the same EGA. The agreement is less satisfactory for the free surface elevation at mid-section where time variations are small. Spectral analyses show that the whole frequency content is preserved (we focus on the first five modes). The same conclusions are drawn for all the types of motion and ART tested. Figure 6 compares results for the rectangular ART forced with pure sinusoidal sway and roll motions with the same EGA. Figures 7 and 8 display irregular motions with the same EGA respectively for the rectangular ART and the ART with the vortices. It results that the sloshing of any ART device is driven by a unique value of EGA.

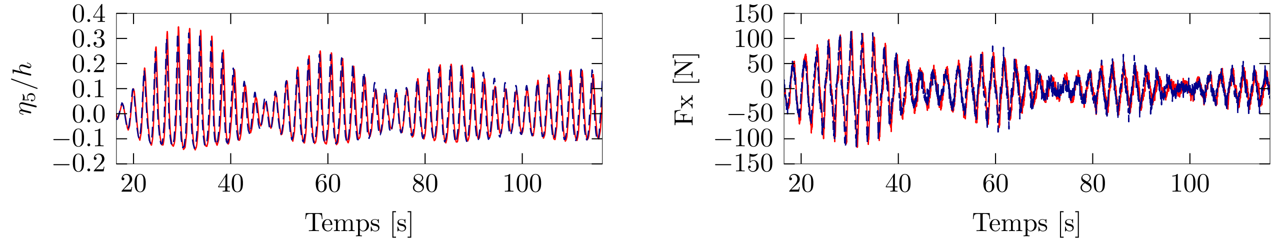

FIGURE 6 – Rectangular ART : Comparison between the pure sinusoidal roll motion of amplitude $R_x = 0.5$deg (red line) and its equivalent pure sinusoidal sway motion of amplitude $T_y = 10.902$mm (dotted blue line) at $f/f_1 = 1.121$. (At left) Time series of the free surface elevation at $x/L = 0.475$ (At right) force F_y. A nonlinear beating as described in Faltinsen [9] is observed.

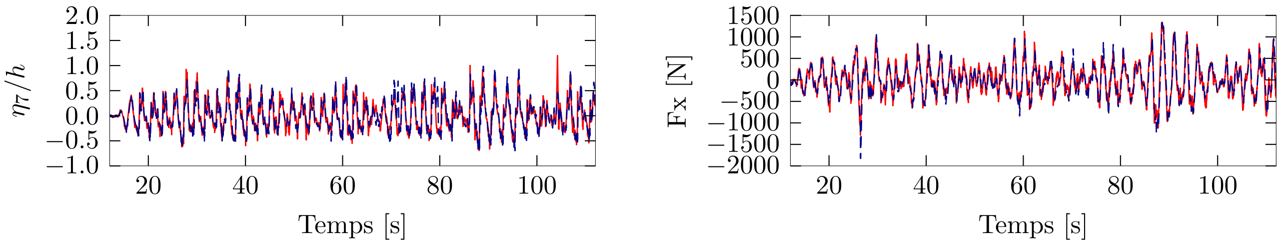

FIGURE 7 – Rectangular ART : Comparison between a 6DOF irregular motion and its equivalent irregular pure roll motion (dotted blue line). (At left) Time series of the free surface elevation at $x/L = -0.375$ (At right) force F_y.

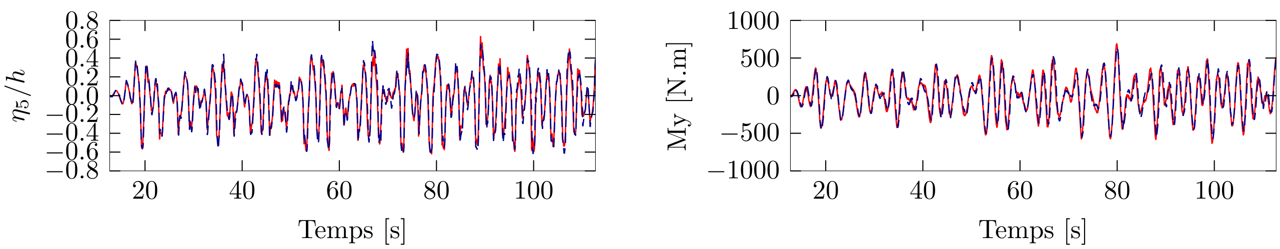

FIGURE 8 – ART with bathtub vortex : Comparison between a irregular roll motion and its equivalent irregular sway motion (dotted blue line). (At left) Time series of the free surface elevation at $x/L = 0.475$ (At right) moment M_x.

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