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Effect of Liquid Viscosity on Sloshing in A Rectangular Tank

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ABSTRACT : Liquid sloshing was investigated for a moving partially filled rectangular tank with/without vertical baffles. A set of experiments was conducted using two types of liquids: water and sunflower oil. For these liquids, the effects of varying the external excitation amplitude and the number of vertical baffles on sloshing are discussed. It was found that the mechanical dissipation due to the liquid viscosity has a remarkable influence on the sloshing characteristics.

Keywords: sloshing, viscosity, baffle,hysteresis, particle image velocimetry

I. INTRODUCTION

Liquid sloshing is of significance in flow physics and in a wide range of applications such as liquid-carrying vehicles, space vehicles, and cargo ships. Many types of liquids such as water, oil, and liquefied natural gas are used in these applications. Fluid motion in a tank partially filled with liquid can impose large structural loads if the period of the tank motion is close to the natural period of the fluid inside the tank. A variety of investigations of sloshing has been studied numerically and experimentally over the past few decades, and these studies have explored significant phenomena such as the linear and nonlinear sloshing effects of the sloshing wave. Early analyses of sloshing were simply linear, weakly nonlinear and inviscid analyses [1]. In the years following 1990, fully nonlinear free surface boundary conditions, complete primitive Navier-Stokes equations, and fluid viscosity have also been considered in the published studies. Baffles are efficient inner structures for suppressing resonant sloshing. Wu et al. numerically predicted the effect of bottom-mounted vertical baffles on liquid sloshing in a rectangular tank and observed vortex shedding near the baffle tip [2]. Various experiments have been carried out to estimate the pressure on the tank walls and the free surface displacement of water from a mean static level. Akyildiz et al. experimentally investigated the pressure distribution in a tank with baffles and concluded that baffles significantly reduce the fluid motion [3]. Zou et al. experimentally investigated the effect of viscosity on sloshing in a tank without baffles and showed that the viscosity of the liquid has an important effect on the sloshing pressure [4].

To reduce the damage caused by the sloshing, many studies of sloshing have been conducted with water as the working fluid. On the other hand, the effects of viscosities of liquids other than water on sloshing are rarely reported. Many works have been devoted to the investigation of the effect of baffles on reducing the sloshing effects. However, the mechanism whereby sloshing due to the baffles and liquid viscosity is damped is not fully understood. In the present study, the effects of varying the external excitation amplitude and the number of vertical baffles on sloshing in a rectangular tank were examined both experimentally and numerically. The vertical baffles are fixed to the bottom of a tank, which is excited with a given excitation frequency. To investigate effects of the viscosity of the liquid, two fluids are considered: water and sunflower oil. Section Ⅱ introduces the experimental method. Section Ⅲ describes the numerical and experimental results, and Section Ⅳ presents the concluding remarks.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

In this study, a rectangular tank partially filled with liquid was actuated by a sinusoidal vibrating shaker table. Fig. 1 shows a schematic view of the experimental setup that consisted of a function generator, vibrating shaker, shaker table, tank, and laser displacement sensor. The dimensions of the tanks with/without the baffles were the same, being 310 mm in length (L), 240 mm in height (H), and 140 mm in width. The still water depth h_0 may range from 50 mm to 70 mm from the bottom of the tank. The horizontal motion of the tank was given by a sinusoidal wave, $X(t) = A_e \sin(\omega_e t)$, where A_e and ω_e were the amplitude and angular frequency of the external excitation, respectively. The laser displacement sensor was used to extract the vibration parameters (frequency and amplitude).

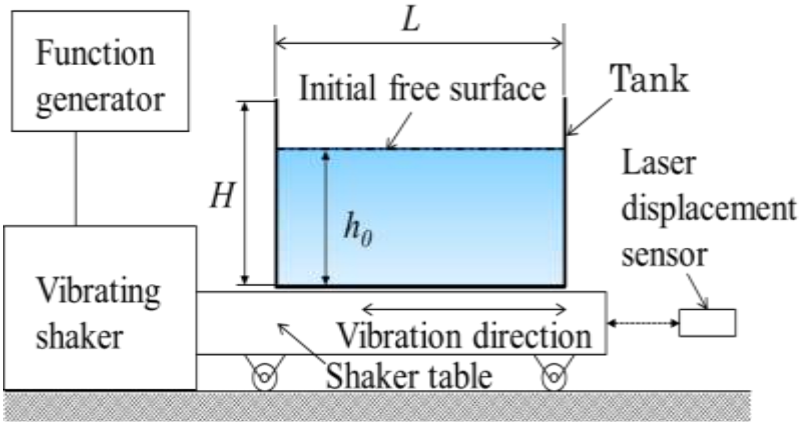

Fig. 1: Experimental apparatus.

Two types of liquids were considered in this study, in order to investigate the effect of the viscosity on sloshing. The first liquid is water. The second is sunflower oil, which is 50 times more viscous than water. Table 1 lists the physical properties of the two liquids. These liquids can be considered Newtonian over the temperature range that we examined. All experiments were conducted at room temperature (22°C ±3°C) and under atmospheric pressure.

Table 1: Physical properties of liquids: ρ = density, μ = dynamic viscosity, ν = kinematic viscosity, σ = surface tension.

	ρ (kg·m^{-3})	μ (Pa·s)	ν (m^2·s^{-1})	σ (N·m^{-1})
Water	998	8.94×10^{-4}	8.96×10^{-7}	0.072
Sunflower oil	900	0.045	5×10^{-5}	0.033

Planar two-dimensional particle image velocimetry (PIV) was used to determine the *U* and *V* velocities in water. Spherical particles made of a synthetic polymer with an average diameter of 90 μm and a density of 1010 kg/m^3 were used as tracer particles for the PIV measurement. A light sheet formed by a continuous YAG laser (wavelength: 532 nm) was used to illuminate the particles seeded in the tank. The positions of the particles were recorded using a high-speed digital video camera, operating at 1000 frames per second (fps) in this study. FlowExpert, a commercial PIV software, was used to measure the two-dimensional time-dependent velocity fields. A high-speed digital video camera was used to capture the free surface motion of the liquid.

III. RESULTS AND DISCUSSION

3.1 Sloshing in Rectangular Tank without Baffles

The free surface elevation η is highly dependent on the amplitude and forcing frequency of the tank motion, liquid depth, liquid properties, and tank geometry, where $\eta = h - h_0$ and *h* is the water depth. The natural frequencies of the sloshing response in a rectangular tank without baffles can be calculated by using the following equation [5]:

$$\omega_n^2 = gk_n tanh(k_n h_0),\ k_n = (2n-1)\pi/L,\ n = 1,2,3, \quad \cdots(1)$$

whereω_n is the angular frequency, *g* is gravitational acceleration, k_n is the wave number, *L* is the length of the tank, and the subscript *n* denotes the *n*-th sloshing mode. The case of *n* = 1 corresponds to the fundamental natural frequency ω_1. The influence of the excitation amplitude on the wave elevation is investigated in the vicinity of the fundamental natural frequency of both water and the oil. The experiments were carried out by starting the oscillation of the shaker table at a frequency considerably lower than the fundamental natural frequency. Resonance occurs when the exciting frequency is close to the fundamental natural frequency. The sloshing in the tank was allowed to attain the steady state prior to taking the data following each change in frequency. For each frequency, the steady state was ensured by allowing sufficient time to elapse (approximately 3 min) before measurements were taken. Then, the excitation frequency was increased incrementally. After the steady state was attained, the measurements were repeated. This process was repeated until the excitation frequency was sufficiently higher than the fundamental natural frequency. The process was reversed by incrementally reducing the excitation frequency. It should be noted that, during the entire procedure, the tank was continually subjected to forcing and the excitation amplitude was held constant; only the excitation frequencies were changed incrementally.

Fig. 2 shows the frequency response of the free surface elevation at the right wall in an unbaffled tank for water and the oil when h_0 = 50 mm and A_e= 0.5 mm. Arrows in this figure show the directions of frequency increase and frequency decrease. When the tank is filled with water, the free surface elevation changes drastically at an excitation frequency of around 1.08 Hz, regardless of whether the frequency is increasing or decreasing. The hysteresis behavior can be clearly observed under this experimental condition. The hysteresis in the sloshing of shallow water in a horizontally excited tank was explored experimentally [6]. On the other hand, the free surface elevation in the tank filled with the oil is extremely low compared to that filled with water. Energy dissipation due to viscous friction leads to a reduction in the wave elevation.

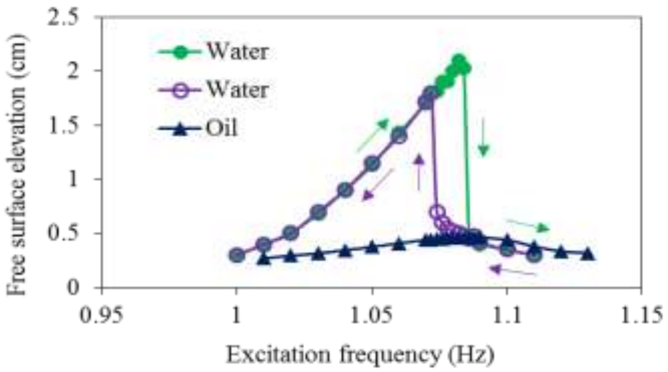

Fig.2: Free surface elevation as a function of excitation frequency at right wall of tank without baffle when h_0 = 50 mm and A_e = 0.5 mm in the cases with water and the oil. The solid circles indicate an increase in the frequency while the open circles indicate a decrease in the frequency in the case of water. The triangles indicate an increase and a decrease in the frequency for the oil.

Fig. 3 shows the frequency response of the free surface elevation at the right wall of an unbaffled tank for the oil when h_0 = 70 mm. It can be seen that no hysteresis is observed under different excitation amplitudes (A_e = 0.5, 1.0, 1.5, and 2 mm) and as the excitation amplitudes increases, the corresponding resonant frequency increases accordingly.

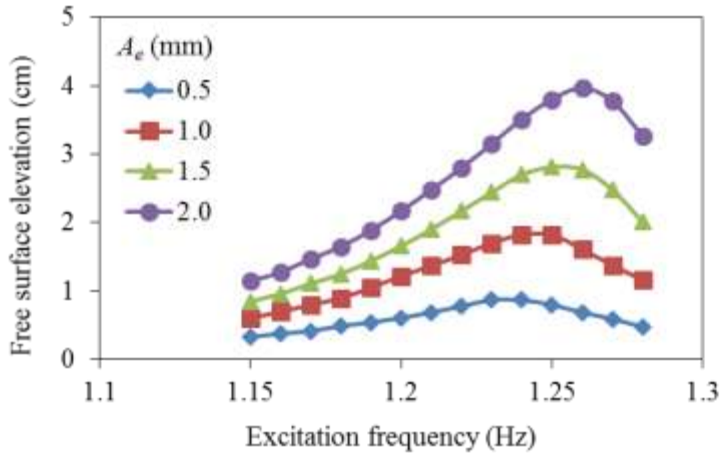

Fig.3: Free surface elevation as a function of frequency at right wall of tank without baffles for different excitation amplitudes when h_0 = 70 mm (with the oil).

In Fig. 4, we can observe a relationship between the maximum relative free surface elevation (η_{max}/A_e) and the excitation amplitude. The maximum free surface elevation η_{max} is taken as the sloshing amplitude before the sloshing wave responds violently due to the occurrence of wave-breaking and three-dimensional effects at the right wall of the rectangular tank. The maximum free surface elevation obtained with the oil is much lower than that obtained with water. When the liquid viscosity increases, the damping effect due to mechanical dissipation is more significant. In addition to the experimental results, the numerical results are also plotted in Fig.4. The numerical simulation was carried out by using OpenFoam [7]. The physical properties of liquids used in the numerical simulation are listed in Table 1. The numerical results are identical to those obtained by experiment in the case of water. On the other hand, the numerical results are slightly lower than the experimental ones in the case of the oil.

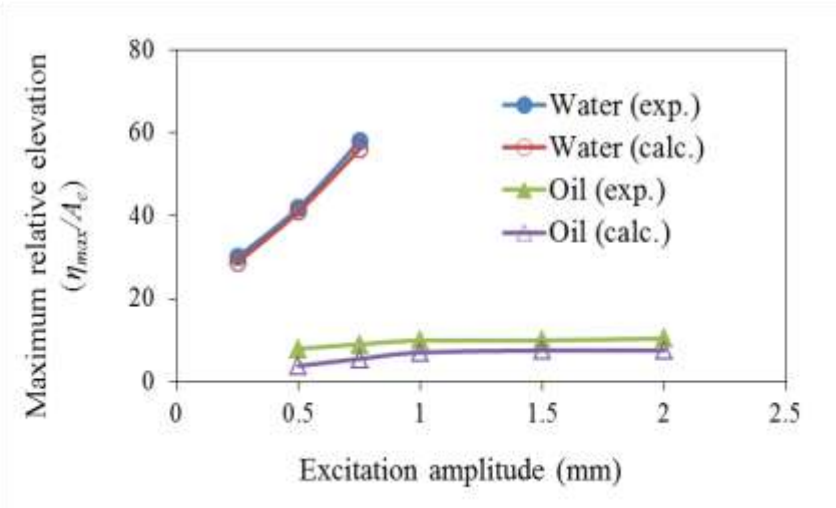

Fig.4: Maximum relative free surface elevation as a function of excitation amplitude at right wall of tank without baffle when h_0 = 70 mm (for water and the oil).

3.2 Sloshing in Rectangular Tank with Baffles

This section discusses the effects of the number of baffles on liquid sloshing in a rectangular tank. Sketches of the baffle arrangements are shown in Fig. 5. For every case considered in this study, the dimensions of the baffles are all the same, that is, 15 mm in height (h_B) and 140 mm in width. The width of the baffles is equal to that of the tanks. All of the baffles are attached vertically to the bottom and are assumed to be rigid. The *x-y* Cartesian coordinates are fixed to the tank and the origin of the coordinates is set at the center of the bottom of the tank.

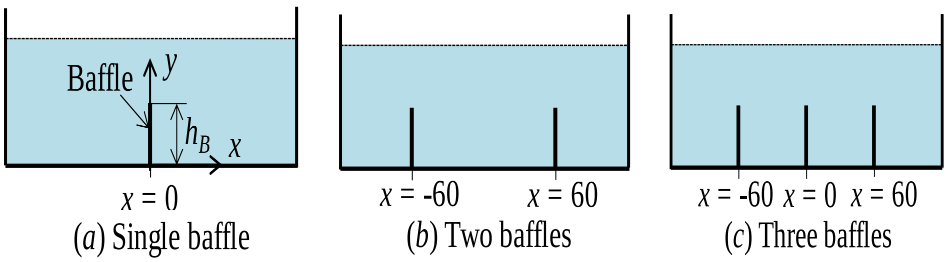

Fig.5: Baffle arrangements (Units: mm).

Fig. 6 shows the free surface elevation in the tank with/without baffles as a function of the excitation frequency when h_0 = 70 mm and A_e = 2 mm. As shown in Fig. 6, the maximum free surface elevation in the tank with baffles is lower than that of the tank without baffles. Furthermore, it can be observed that the resonant frequency in the tank with baffles is smaller than that in the tank without baffles.

Fig. 7 shows the relative free surface elevation as a function of the excitation frequency in a tank with a single baffle at different excitation amplitudes for the oil. As is shown in Fig. 7, it can be seen that the resonant frequency is hardly affected by the excitation amplitude. In contrast, the relative elevation around the resonant frequency is greatly influenced by the excitation amplitude. Furthermore, it seems that the relationship between the excitation amplitude and relative elevation is nonlinear.

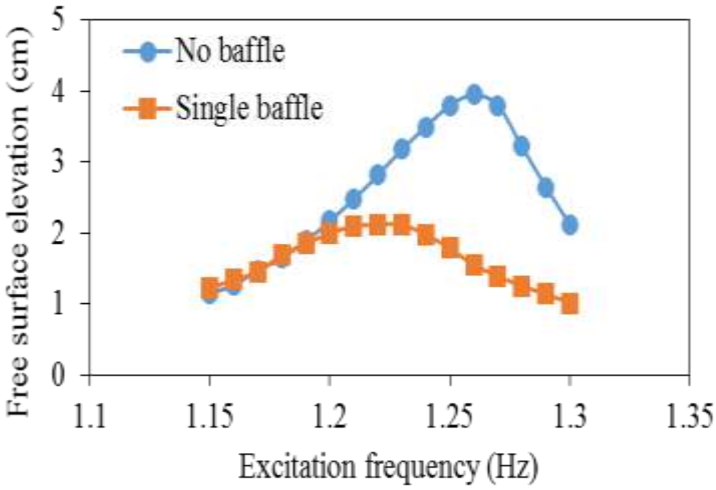

Fig. 6: Free surface elevation as a function of excitation frequency at right wall with/without baffles when h_0 = 70 mm and A_e = 2 mm (with the oil).

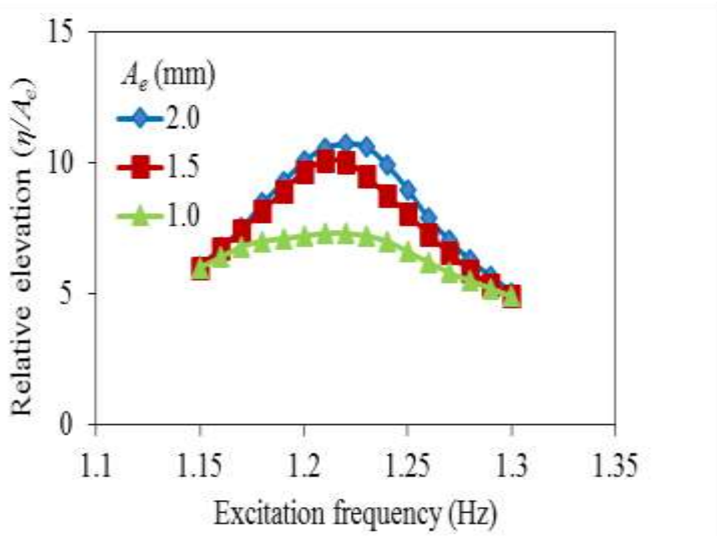

Fig.7: Relative free surface elevation as a function of excitation frequency at right wall of tank with single baffle under different excitation amplitudes when h_0 = 70 mm (with the oil).

Baffles are widely used as slosh suppression devices in liquid storage containers. The efficacy of the damping depends on the dimensions and positions of the baffles in the tank. In this study, the effect of vertical baffles on the slosh response was investigated by varying their numbers and positions. Fig. 8 shows the free surface elevation as a function of the excitation frequency in a tank with baffles. The arrangements of the baffles in a tank are shown in Fig. 5. It can be seen that the maximum free surface elevation decreases as the number of baffles increases. The differences in the surface elevation are probably due to the blockage effect of the baffles on the liquid convection, as well as the effect of the vortices on the energy dissipation of the sloshing wave. The resonant frequencies, as determined by the number of baffles mounted on the tank bottom, are not exactly the same.

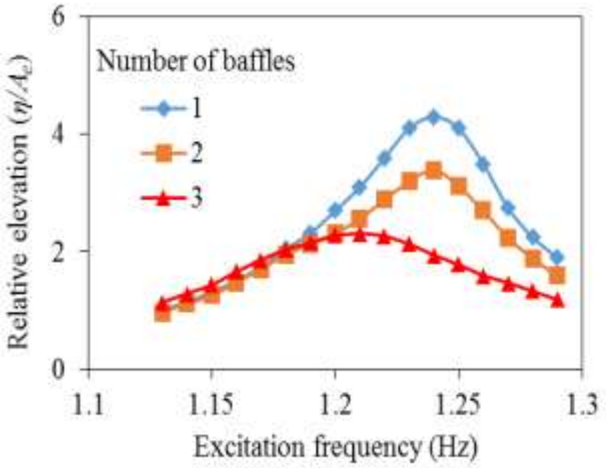

Fig.8: Relative free surface elevation as a function of excitation amplitude with different numbers of baffles when h_0 = 50 mm and A_e = 2 mm (for water).

Fig. 9 shows the relative maximum free surface elevation as a function of the excitation amplitude at the right wall of a tank with a single baffle when h_0 = 70 mm for both water and the oil. It can be observed that the relative maximum surface elevation increases almost linearly over the measured range of the excitation frequency.

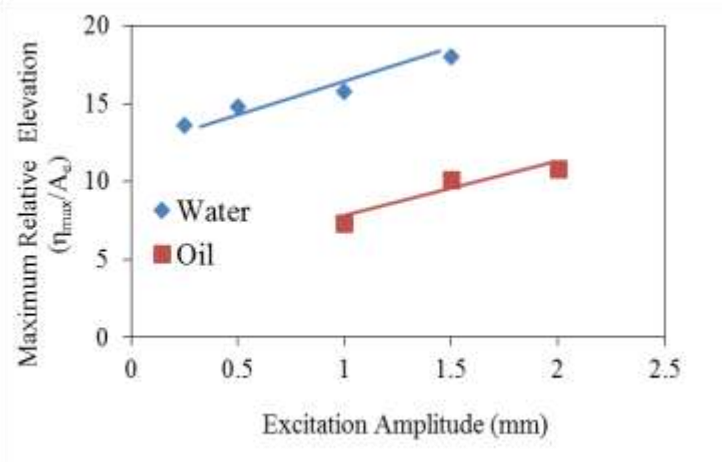

Fig.9: Relative maximum free surface elevation as a function of excitation amplitude at right wall of tank with single baffle when h_0 = 70 mm (both water and the oil).

PIV measurements were carried out in all regions except very close to the bottom of the tank, in order to avoid the scattering of the laser light as a result of reflection from the bottom surface of the tank. Fig. 10 shows the velocity vectors and vorticity contours obtained by PIV in tanks with different numbers of baffles at time of T/4 where T is a stable sloshing period. As the wave sloshes from right to left, clockwise circulation vortices occur at the right of the baffle' tips. As the number of baffles increases, the size and strength of the vortices caused by liquid flow separation from the baffle tip becomes smaller and weaker. The stronger vortices will cause greater energy dissipation of the sloshing waves while suppressing the sloshing displacement. In the wall-bounded sloshing flow, the enstrophy density Φ will play the most important role in the mechanical energy dissipation. For the two-dimensional case, Φ is equal to $|\omega_z|^2/2$, where ω_z is the vorticity around the axis perpendicular to the *xy*-plane. The stronger mechanical dissipation can be observed in the neighborhood of the baffles and the hydrodynamic interaction of the vortices with the baffles barely occurs in the case with two or three baffles, as shown in Fig. 10. The occurrence of the hydrodynamic interaction of vortices between the baffles is related to the distance between the baffles. The details of the hydrodynamic interaction of the vortices will be discussed in a future investigation.

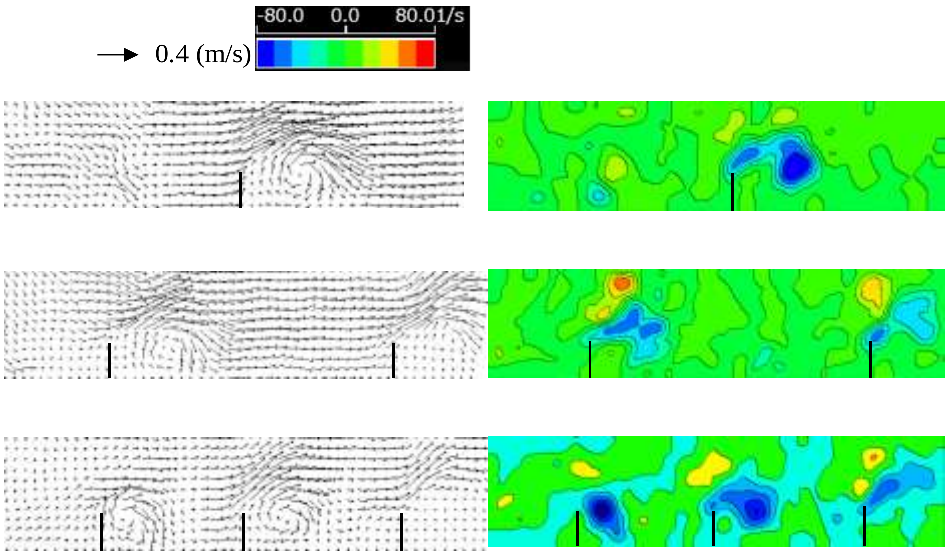

Fig. 10: Velocity vectors (left) and vorticity contours (right) obtained by PIV in the vicinity of baffles at $T/4$ when h_0 = 60 mm, ω_e = 7.5 rad/s, and A_e = 2 mm (with water).

The vorticity contour in a tank with three baffles, obtained numerically using OpenFoam, is depicted in Fig. 11 under the same operating conditions as those shown in Fig. 10. It can be seen that the numerically obtained vorticity contour shown in Fig. 11 is slightly different from that obtained experimentally and shown in Fig. 10. Strong shear layers are formed on the bottom of the tank, as shown in Fig. 11.

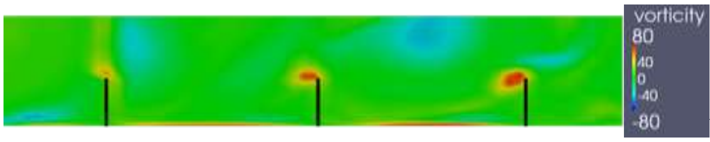

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Fig. 11: Vorticity contour obtained numerically by OpenFoam in the vicinity of the baffles at $T/4$ when h_0 = 60 mm, ω_e = 7.5 rad/s, and A_e = 2 mm.

IV. CONCLUSIONS

The objective of this study was to investigate, experimentally and numerically, the effect of liquid viscosity on sloshing in a tank with/without vertical baffles. In particular, the wave response near the resonant frequency was investigated using water and sunflower oil.

Some of conclusions can be summarized as follows:

(1) By incrementally increasing or decreasing the excitation frequency, hysteresis phenomena were observed near the resonance frequency in the experiment with water. They were not with the sunflower oil.
(2) With an increase in the excitation amplitudes, the corresponding resonant frequency increases accordingly in a rectangular tank with/without baffles in the case of sunflower oil.
(3) The maximum free surface elevation decreases as the number of baffles increases.
(4) The relative maximum surface elevation increases almost linearly over the excitation frequency measured in a rectangular tank with a single baffle.
(5) The velocities in a rectangular tank with/without baffles were measured by using particle image velocimetry (PIV) in the case of water. It was observed that stronger vortices occurred in the neighborhood of the baffles in the tank as the number of baffles was decreased.
(6) The numerical results show that strong shear layers are formed at the bottom of the tank.

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