Experimental investigation of sloshing in the rectangular tank under the hydrophobic effect

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Abstract. Liquid sloshing causes ship tank's surface to be damaged. In this study, this phenomenon was analyzed experimentally in rectangular tank model. Partially filled tank has been experienced and it was excited at single frequency range by direction of sway. Experiments were carried out with uncoated and hydrophobic coated tank. Only one water level was chosen for demonstrate sloshing effects on the different tank surface parameters. Wave path, wave breaking and shape of wave during flip-through were cough by high speed camera images. Strain gages have also been implemented to lateral side of tank to show local reaction of structure by measuring liquid induce deformation. Besides that, all experiments have been repeated by changed surface parameters at two contrast lateral sides on tanks. The surface parameter has been modified by applying hydrophobic coat. The coated surfaces propose to increase degrees of the contact angle between water drop and structure surface. The comparisons have been conducted within considering the images and measured results in coated, non-coated surface at tank sloshing experiments. The results show that the hydrophobic surface decreased the sloshing force on lateral sides, wave propagated more splay and water couldn't reach the level of wave as non-coated surface.

Keywords. Ship tank, sloshing, hydrophobic

1. Introduction

Sloshing forces is the main concern at partially filled tanks. The external force causes free surface deformations, these exited fluid impacts the wall of tanks and causes the instability. These fluid motions have three types of shapes during interaction lateral surface: standing waves, broken waves and waves in process. The characterizations of wave are variable by excitation frequency, rate of height of fluid and length of tank. Colagrossi et al [1] studied the sloshing by considering one rate of height of fluid and length of tank experimentally. The free surface deformation was tracked and also applied the pressure sensor on lateral side of the tank then presented the measured pressure values. Souto-Iglesias et al. [2] investigated sloshing problem by using the rectangular tank. Two fluid types were applied for various Reynolds number levels. Also three dimensionality were investigated by using four width size rectangular tanks. During sloshing experiment, wave takes standing wave shapes when natural frequency and forced frequency closes each other. This interaction occurs by lateral side together

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with more air pocket and this case is discussed in detail. In addition, Wood et al. [3] studied air cushion's effect on wave impact through the wall by pressure impulse theory. Sloshing is also important for ship stability. Pistani and Thiagarajan [4] investigated the sloshing pressure by analyzing fluid behavior in model LNG tanks. Several pressure sensor was mounted on the tank surface and wave images were recorded. Then measured values were obtained from experiments at various impacts and capture images during sloshing were highlighted. Recording sloshing experiments support to understand this phenomenon by the free surface deformation and interaction wave through side walls images. Tosun et al. [5] tracked the wave motions using camera and developed a method that is determined the lateral force by using images. Lugni et al. [6] investigated the sloshing with focusing on flip-through event. The analyzation was carried out images and was discussed the air cushion effect. Kim et al. [7] presented the two scaled model test and they compared these models by peak pressure value. Celis et al. [8] is validated the computational code for dam breaking and sloshing by experimental data.

The wettability ratio is an important parameter in fluid structure interaction problems such as sloshing. This ratio can be changed with hydrophobic coating, which increases the contact angle between fluid and solid so that the surface becomes more water repellent. Daniello et al. [9] stated that a hydrophobic surface reduces the drag in microscale flows for both laminar and turbulent flow regimes. Korkmaz and Guzel [10] carried out slamming experiments with cylinders and spheres, and observed huge differences during the impacts of these objects with hydrophobic surfaces. They found that the pressure distribution on the wetted length change drastically under hydrophobic effects.

This study focuses on is to measure the strain on the lateral side of tank and record the process of wave phases at sloshing experiment and then show the effect of hydrophobic surface.

2. Experimental Setup

The way of investigation the sloshing phenomena was conducted by transferring water from one side to the other side. The tank was mounted on slidable plate. Other materials such as 220V AC induction motor with integrated frequency inverter, data logger, high speed camera and computer were connected together as shown in Figure 1. The periodic motion for rectangular tank, which is demonstrated in figure 2, sloshing frequency is calculated in Eq. 1 by linear potential theory.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{n\pi}{L} g \tanh\left(\frac{n\pi}{L}\right)} \quad (1)$$

Here h is water height, n is model number, g is gravity and L is length of tank. In this experiment, the tank water level is 10.8 cm and the ratio of h/L is 0.3. The tests were also visualized using phantom miro eX4 series high speed camera with applying 1000 fps. The camera was placed in front of the tank and led light was located in front of the camera. Thus, the wave, breaking wave and its process, the wave run-up and down were captured. The image process was performed in order to analysis the video record. All tests triggered the same initial position and three minutes were waited to obtain the rest situation before starting new experiment. The effect of hydrophobicity was performed by applying the hydrophobic coat to the lateral sides. Thus tank lateral wall gained water repelling specification.

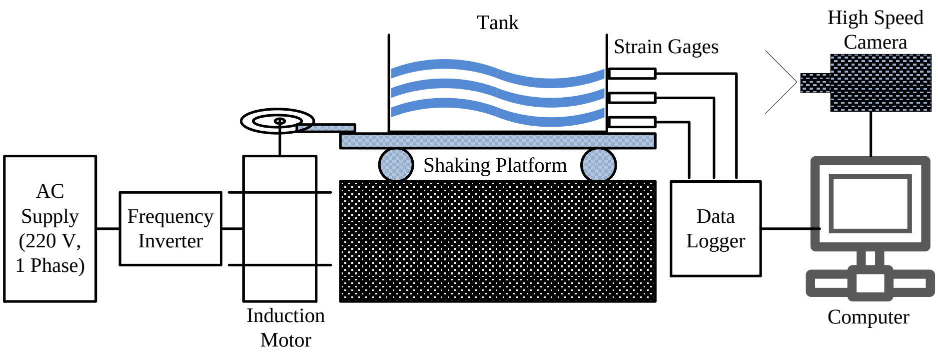

Figure 1. The experimental setup of sloshing mechanism

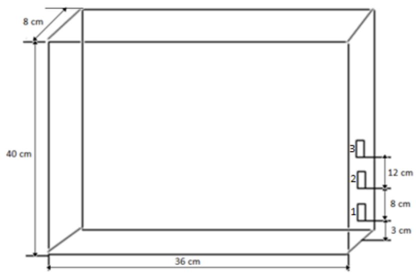

Figure 2. The ship tank dimensions and the locations of strain gages

A hydrophobic coating by Wetproof Inc. was applied onto the test bodies to create hydrophobic surfaces. This coating does not change the dimensions of the side walls because of the micrometer level thickness of the coating application.

Three Strain gages are applied the lateral side of the tank to measure strain on side structure during sloshing experiment. First, the excited tank tests on sway motion were carried with untreated surfaces. Then the tests were repeated under the same hydrodynamic conditions with hydrophobic coated surfaces.

3. The Experimental Results and Discussion

Even though, some studies are available hydrophobicity about fluid structure interaction, the effect of surface parameters on sloshing has not been reported in detail. The water is selected as liquid in the experiments to demonstrate the hydrophobicity effects. The properties of liquid are given in Table 1.

Table 1. The properties of liquid used in the experiments

Liquid	**ρ (kg/m^3)**	**μ (kg/ m/s)**	**ν (m^2/s)**	**σ (kg/s^2)**	**C_S(m/s)**
water	998	8.94e-4	8.96e-7	0.0728	1480

The Reynolds number using with propagation speed by applying transitional water Airy formula is defined in Eq. 2.

$$U = \frac{gT}{2\pi}\tanh(kH) \tag{2}$$

Here T is period, g is gravity, by considering the water depth H as a prediction of the order of wave amplitude and k wave number can also be estimated by twice tank length. The wave characterizes as transitional water when the 0.04<H/L<0.5 ratio occurs. Here in this study, the H/L ratio is 0.3 and T is 4.54 sec.

Reynolds number in lateral impact is determined in Eq. 3.

$$\mathrm{Re} = \frac{H}{\nu}\frac{gT}{2\pi}\tanh(kH) \tag{3}$$

Here ν is kinematic viscosity.

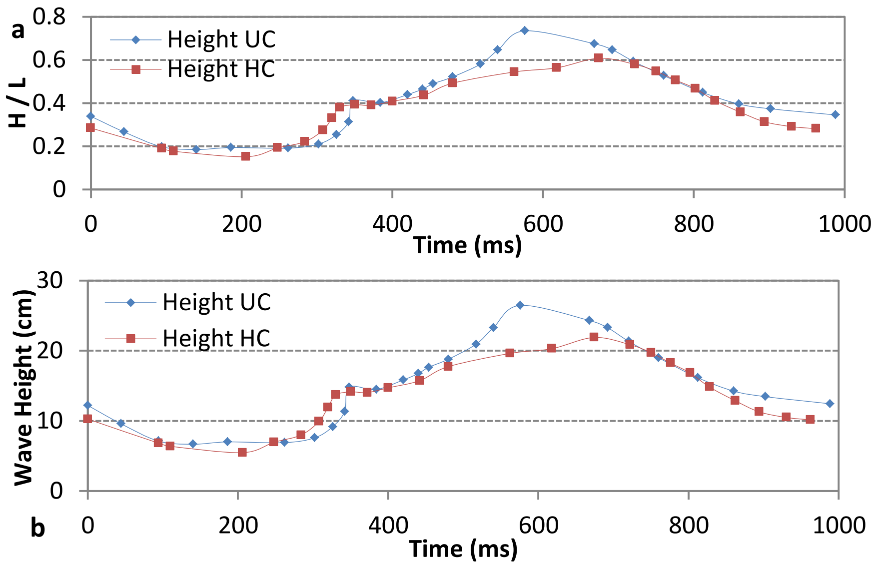

Figure 3. Time history of wave evaluation under the uncoated (UC) and hydrophobic coated (HC) lateral surfaces. (a) is dimensionless values, (b) is wave height with a function of time

Figure 3 shows time history of wave evaluation under the uncoated and hydrophobic coated lateral surfaces at sloshing experiments. One point is selected on tank surface and then wave height is tracked at that point for one cycle. This free surface deformation shows quite differences especially on main wave mass. Both experiments were excited the same frequency, but the different shape occurred because of the side wall property differences. For this excited frequency, the gap reached by 4.5 cm.

The Reynolds Number was calculated around 14000 for the uncoated case. However, it decreased to 7000 at hydrophobic coated case because of the changing amplitude. Both Reynold numbers are demonstrated the flow regime as turbulent clearly. Even, properties of the tank are same except the surface parameter; it is shown that Reynolds number can change by hydrophobic coat.

The conservation of energy indicates us that the rate of change of the energy within the fluid plus the energy loss is equal to energy which is given from drive mechanism. Initially, same sway motion and frequency is given to tank under uncoated and coated lateral wall. But, energy dissipation is different at wave evaluation and impact on walls during sloshing experiments. Figure 4 illustrates the instant wave shapes for different time steps with non-dimensional values. The deformation free surface at x and y direction are nondimensionalized by length of tank and height of water respectively. The figure 4(b) demonstrates that the wave couldn't run up through the wall as much as non-coated because of the water repelling effect of the hydrophobic wall.

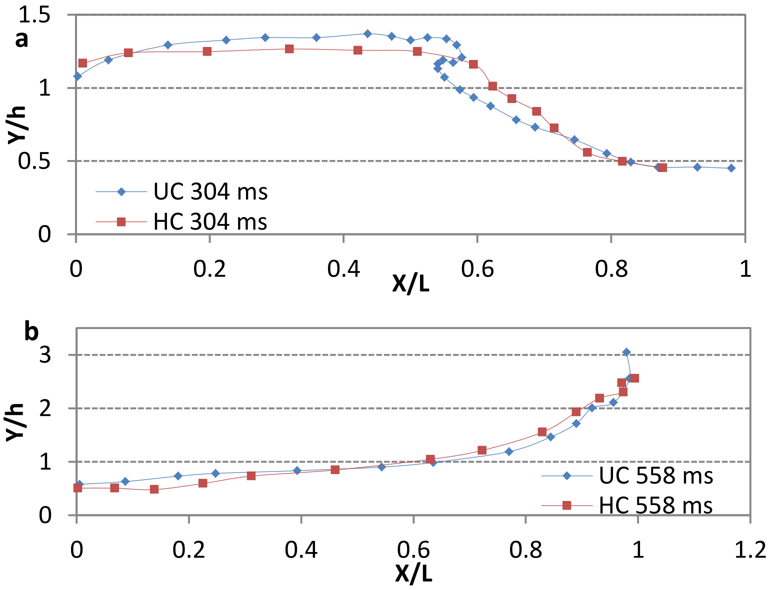

Figure 4. Instant wave shapes for uncoated (UC) and hydrophobic coated (HC) tank at different time steps with dimensionless values

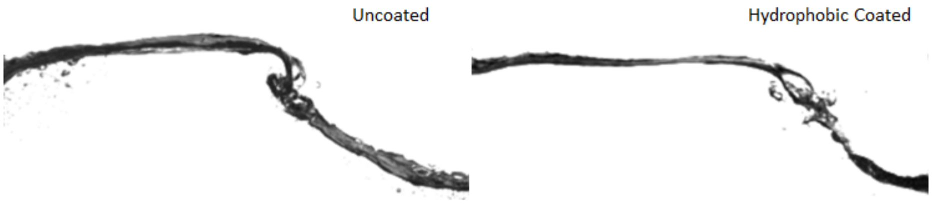

Figure 5. Free surface behaviors at the same time (304 ms) and position under uncoated and hydrophobic coated cases in the tanks

Figure 5 show that the instant images of free surface behavior which is depicted at figure 4 (a). In this chosen frame shows that the wave is in developing of breaking stage at on uncoated case, but the wave takes gentle slope shape at the same time on hydrophobic case. These shape differences show that the more fluid mass was pushed so more energy transferring was occurred at hydrophobic coated case.

Beyond these results, sloshing experiments is also applied to measure the strain on lateral wall. The tagged of 1, 2 and 3 strain gages are equipped on the wall starting from deeper to the upper tank sides, respectively. The same excitation frequency was applied to the tank. Then the effects of fluid on lateral structure were measured from strain gages for both uncoated and coated cases. Figure 6 shows the discrepancy of the first strain values that are observed as %12. Furthermore, the maximum strain value rises up more precisely at uncoated one. Contrary, this measured strain shape is more horizontally at coated tank. Second peak is also observed and this value is more than first peak at hydrophobic coated tank. These behaviors of strain values are caused by changing wave form. Interestingly the behavior alteration of wave is more effective on strain 2. Almost half of impact disappeared. The measured values of third strain values on the vertical wall, it is again decreases almost same percentage as strain 1. This results show that the surface features can change water wave characterization of evolution and moreover the structure response can change due to water impact.

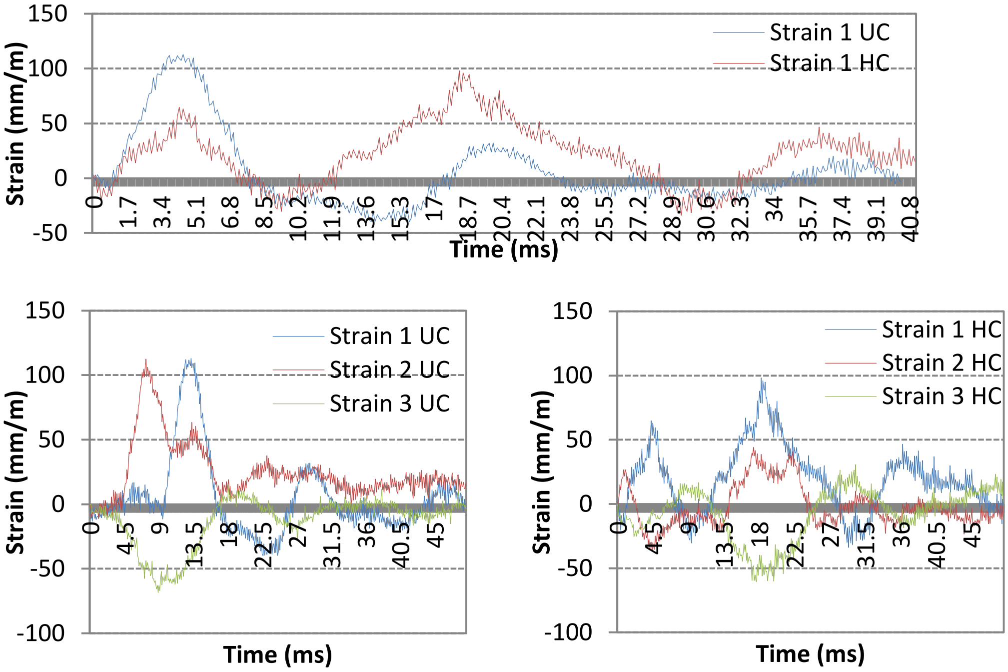

Figure 6. The effects of fluid on lateral structure were measured from strain gages for both uncoated (UC) and hydrophobic coated (HC) cases.

4. Conclusions

In this study, the preliminary sloshing experiments were carried out for determining the lateral impact at selected frequency exited. The strain values and wave evaluations were analyzed by generated sway motion at rectangular tank. The local water stress on structure was measured by the strain gages and high speed camera was the way of getting through the water motions. All experiments were also performed for hydrophobic coated lateral walls of tank. The effects of coated structure on sloshing were interpreted with strain measurement and captured images. The comparisons have been provided that the impact is decreases by hydrophobic coat. The inspection of image process shows the wave evaluations are alter so wave breaking, standing waves and wave in processes stages are changed. Furthermore, the analysis of strain data put in support arguments to demonstrate the hydrophobic coated effect by decreasing peak value of impact.

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