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Baffle-based Sloshing Mitigation Technique for Liquid Storage Tanks

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Abstract- This study focused on sloshing mitigation technique for a liquid storage tank. An experimental apparatus was manufactured to allow a predetermined vibration condition to the tank. The mode shape and natural frequency of sloshing were determined by observing the liquid motion in the tank. Baffles were used to mitigate the sloshing of liquid. The amount of liquid and vibration amplitude were used as experimental parameters. The amount of liquid was varied from 30% to 80% of the tank capacity, while the vibration amplitude was varied from 40 mm to 120 mm. For a given amount of liquid, the natural sloshing frequency decreased as the vibration amplitude along the longitudinal direction increased. For a given vibration amplitude, the natural sloshing frequency increased as the amount of liquid increased, but decreased once the amount of liquid exceeded a certain level. The sloshing force at the tank wall increased as the amount of liquid increased. The introduction of baffles was found to be effective to mitigate the sloshing force.

Keywords: Sloshing mitigation technique, Natural sloshing frequency, Vibration amplitude, Amount of liquid, Baffles.

Introduction

When a liquid storage tank is shaken due to unexpected and/or inevitable external forces, liquid stored in the tank will slosh from side to side. This phenomenon, called sloshing, can be easily observed in liquid storage tanks of railroad cars, large vessels, aircrafts, and automobiles. While sloshing does not occur in completely filled tanks, it is easily observed in tanks that did not completely fill, or in those where the free surface of liquid is not confined. In particular, when the vibration frequency approaches the natural frequency of liquid storage tank, sloshing becomes more pronounced. This, in turn, causes a force and moment to the tank wall, which can have serious consequence on the structural stability of the liquid storage tank and may even lead to the instability of a moving vehicle in which the liquid storage tank is installed [1, 2].

Dynamic modeling and analysis of sloshing effect in a fuel tank, which can have a significant influence on the stability of an aircraft, have been performed as a part of the development of space rockets. Such studies include the effect of fuel sloshing on the lateral stability of an aircraft [3], the dynamic effects of suddenly excited bending oscillations on the fuel motion [4], and the measurement of the sloshing frequency, pressure and moment under reduced gravity conditions as well as the determination of the damping coefficient and sloshing control using baffles [5]. Several mathematical models have been proposed as a means of assessing the effect of the fuel sloshing by varying the amount and physical characteristics of the stored liquid as well as the shape of the liquid storage tank [6, 7]. Also, validation studies were performed to identify the sloshing behavior and to develop a means of sloshing mitigation based on experimental and numerical analyses considering the interaction between fluid and tank structure [8-10]. Although sloshing phenomena observed in liquid storage tanks have been analyzed, taking the factors associated with the damping mechanism into account, systematic studies on the sloshing of the stored liquid have yet to be performed, although it is essential to the further development of liquid storage tanks.

For this study, an experimental apparatus, which allows a wide range of vibration conditions to the tank, was manufactured to investigate the sloshing phenomenon in the liquid storage tank. The amount of liquid and vibration conditions such as vibration amplitude and vibration frequency were used as experimental parameters. A method for measuring the sloshing force to the tank wall and several types of baffle were suggested to mitigate the sloshing force. In addition, their effectiveness of the sloshing mitigation of the liquid storage tank was systematically investigated.

Experimental Apparatus

Fig. 1 shows an experimental apparatus used to produce vibrations. It consists of a DC motor, a connecting rod, a crank offset, and a controller. In an earlier version of this apparatus, a stepper motor was used for the application of numerical control and precision actuation. However, the motor was not capable of providing sufficient actuating power when the liquid storage tank with large amounts of liquid slipped off the guided rail of the vibration device while the actuator was operating. For these reasons, a DC motor was used to replace a stepper motor in order to provide sufficient actuating power and easy control.

Fig. 2 shows a cylindrical liquid storage tank with an internal diameter-to-length ratio of 1:3 (internal diameter: 244 mm, length: 732 mm). The tank was made of a transparent acrylic material (thickness: 8 mm) for the visualization of the sloshing in the liquid storage tank. Baffles could be mounted at a point 183 mm (1/4-way point), 366 mm (1/2-way point) and/or 549 mm (3/4-way point) from the right-hand end of the tank. When only one baffle was used, it was installed at 336 mm (1/2-way point), and when two baffles were installed, they were placed at 183 mm (1/4-way point) and 549 mm (3/4-way point).

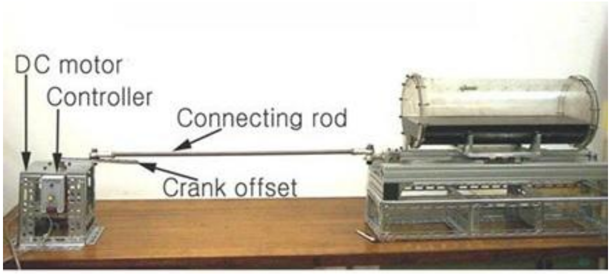


Fig.1. Vibration-producing Device

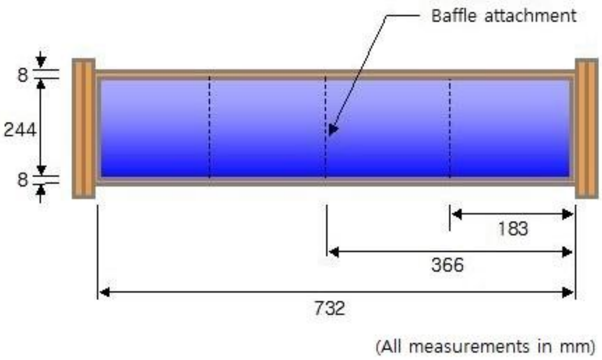
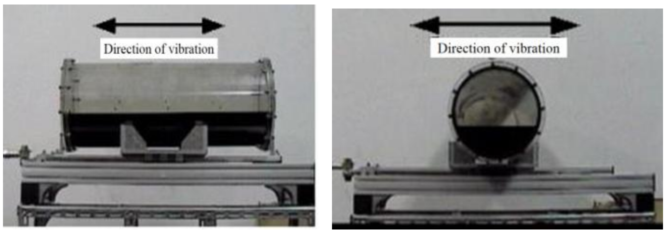


Fig.2. Configuration of Liquid Storage Cylindrical Tank

Evaluation of Sloshing Behavior

The mode shape and natural frequency of sloshing were assessed based on the amount of liquid and the vibration amplitude. The vibration frequency was adjusted by using the controller of the vibration device, while the vibration amplitude was varied by adjusting the length of the crank offset between 40 mm and 120 mm in 10-mm steps. A digital video camera was used to record the sloshing of the stored liquid. Two vibration conditions of horizontal vibration in the longitudinal direction and horizontal vibration in the lateral direction were considered as shown in Fig. 3(a) and 3(b), respectively.



(a) Longitudinal Direction **(b) Lateral Direction**

Fig.3. Vibration Conditions of Liquid Storage Tank

Fig. 4 shows the sloshing of the stored liquid in the liquid storage tank that is 30% full, as caused by horizontal vibration in the longitudinal direction. The vibration amplitude was 40 mm, and the vibration frequency was increased gradually by using the controller. When the liquid storage tank was moved in one direction, the sloshing exhibited a constant slope, as shown in fig. 4(a) to 4(c). When it was then moved in the opposite direction, as shown in fig. 4(d), the slope of the sloshing was bilaterally symmetrical to those shown in fig. 4(c). The mode shape and the vibration frequency shown in fig. 4(c) and 4(d), which exhibited the maximum symmetrical slope, were determined as the first mode shape and the first natural frequency of sloshing, respectively. When the vibration frequency was gradually increased, the degree of sloshing increased, as shown in fig. 4(e) to 4(h). However, above a certain frequency, sloshing with a specific bilateral symmetry was observed, as shown in fig. 4(i) and 4(j). The mode shape and the vibration frequency shown in fig. 4(i) and 4(j) were determined as the second mode shape and the second natural frequency of sloshing, respectively.

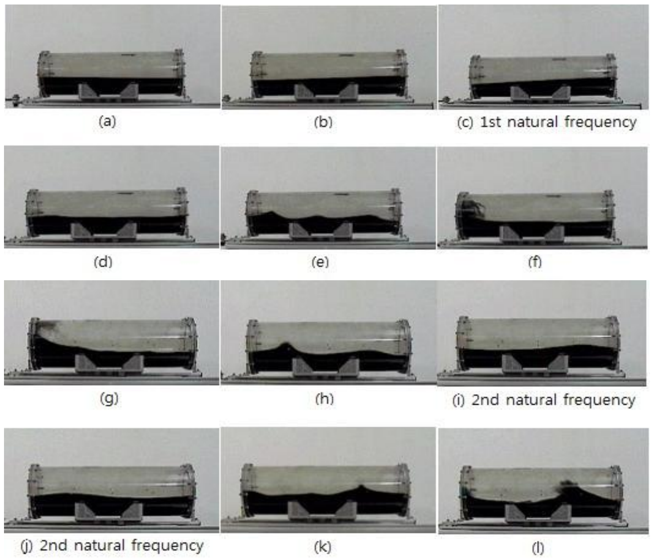
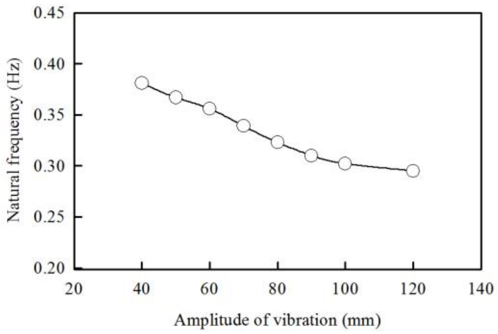


Fig.4. Determination of Natural Frequency of Sloshing Resulting from Horizontal Vibration in Longitudinal Direction

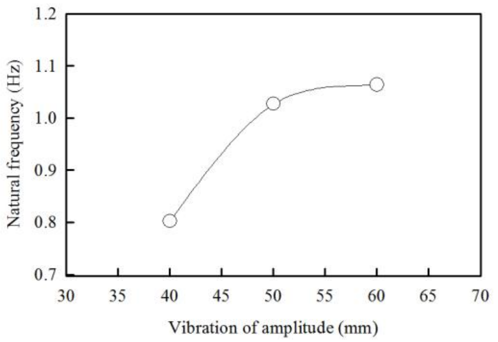
Fig. 5 shows the sloshing of the liquid stored inside the tank that is 30% full, as caused by horizontal vibration in the lateral direction. The vibration amplitude was 40 mm and the vibration frequency was increased gradually using the controller. A gradual increase in the vibration amplitude resulted in the sloshing of the stored liquid that exhibited a bilateral symmetry. The mode shape and the vibration frequency, which exhibited the maximum symmetrical slope, were determined as the first mode shape and first natural frequency of sloshing, respectively. In contrast to the case involving the horizontal vibration in the longitudinal direction, the second mode shape of sloshing was difficult to observe during the horizontal vibration in the lateral direction.

The natural sloshing frequency was examined by varying the amount of liquid and the vibration amplitude. The amount of the liquid was set to be 30% full, while the vibration amplitude was varied from 40 mm to 120 mm, in 10-mm steps. The vibration frequency was increased using the controller and horizontal vibrations in the longitudinal and lateral directions were applied. Fig. 6 shows the variations of natural sloshing frequency in 30% full liquid storage tank subjected to horizontal vibration in the longitudinal and lateral directions while the vibration amplitude was varied. As shown in the figures, the natural sloshing frequency decreased as the vibration amplitude increased in the case of horizontal vibration in the longitudinal direction. However, the natural sloshing frequency increased as the vibration amplitude increased in the case of horizontal vibration in the lateral direction.

Fig.5. Determination of Natural Frequency of Sloshing Resulting from Horizontal Vibration in Lateral Direction



(a) Longitudinal Direction



(b) Lateral Direction

Fig.6. Variations of Natural Sloshing Frequency in 30% Full Liquid Storage Tank

Fig. 7 shows the variations of the first natural sloshing frequency by varying the amount of liquid and the vibration amplitude in the case of horizontal vibration in the longitudinal direction. The amount of liquid was set to be 30%, 50%, 60%, 70%, and 80% full. The vibration amplitude was varied from 40 mm to 120 mm, in 10-mm steps. While the vibration amplitude was constant, the first natural sloshing frequency increased as the amount of liquid increased, but decreased once the amount of liquid in the tank exceeded a certain level. On the other hand, the first natural sloshing frequency decreased as the vibration amplitude increased, regardless of the amount of liquid.

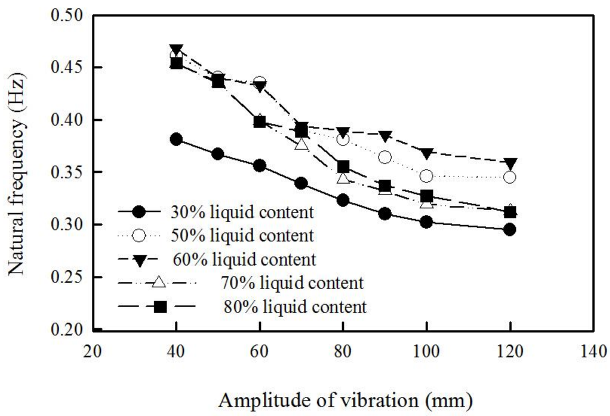


Fig.7. First Natural Sloshing Frequency in 30% Full Liquid Storage Tank by Varying Amount of Liquid and Vibration Amplitude

Sloshing Mitigation Technique

A. Sloshing Force Measurement

Fig. 8 shows an experimental apparatus used to measure the sloshing force at the tank wall. A small-capacity load cell was mounted on the wall to measure the force being applied to the tank wall as a result of the sloshing. The force signals were converted to voltages using an A/D converter (PCI-MIO-16E-1, National Instruments, USA) and a signal amplifier (2100 system strain gage conditioner and amplifier system, Micromeasurements Group, USA). Data was collected at a rate of 50 samples per second.

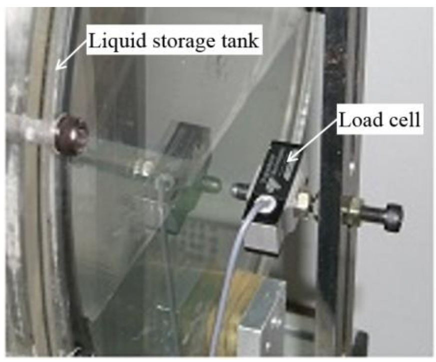
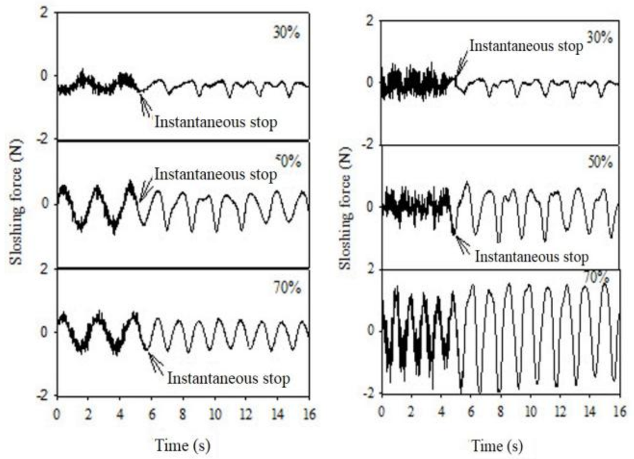


Fig.8. Sloshing Force Measurement

To measure the sloshing force, the liquid storage tank vibrated with constant vibration frequency must be instantaneously stopped so that any forces being generated are a result of the sloshing of the stored liquid only. Fig. 9

shows the sloshing force signals measured by the load cell when storage tanks with 30%, 50%, and 70% full were subject to an instantaneous stop. Fig. 9(a) shows the results vibrated at the first natural sloshing frequency, while Fig. 9(b) shows the results vibrated at the second natural sloshing frequency. These results show that an instantaneous stop after vibrated at the first natural sloshing frequency produced larger force signals in the tank with 50% or 70% full than those in the tank with 30% full. When an instantaneous stop after vibrated at the second natural frequency produced larger force signals in the tank with 70% full than those in the tank with either 30% or 50% full. Based on these results, we can infer that the sloshing force increased as the amount of liquid increased.



(a) First Natural Frequency **(b) Second Natural Frequency**

Fig.9. Sloshing Force Signals at Tank Wall Vibrated at First Natural Frequency and Second Natural Frequency of Sloshing

Fig. 10 shows the variations of the force signals by varying the location of the load cell. The load cell was attached to the side of the tank wall at positions 50 mm, 85 mm, and 130 mm from the bottom of the tank. The following conditions were set for this experiment: the amount of liquid was set to be 50% full, the vibration amplitude was 40 mm, and the vibration frequency was set to be 0.461 Hz, which was the first natural sloshing frequency when the tank is 50% full. These results show that the load cell was closer to the bottom surface, the force signals being applied to the tank wall increased due to a greater amount of liquid acting on the load cell.

B. Sloshing Mitigation Effects

Baffles were installed in an attempt to mitigate the sloshing of liquid in the tank. Fig. 11 shows the four types of baffles used in this study. Type 1 is a hollow baffle with an external diameter of 244 mm and an internal diameter of 122 mm. Type 2 is a Type 1 hollow baffle with twelve 20-mm holes. The Type 3 and Type 4 baffles have sixteen 30-mm holes and twenty-nine 22-mm holes, respectively, such that they have the same effective area as the Type 1 baffle.

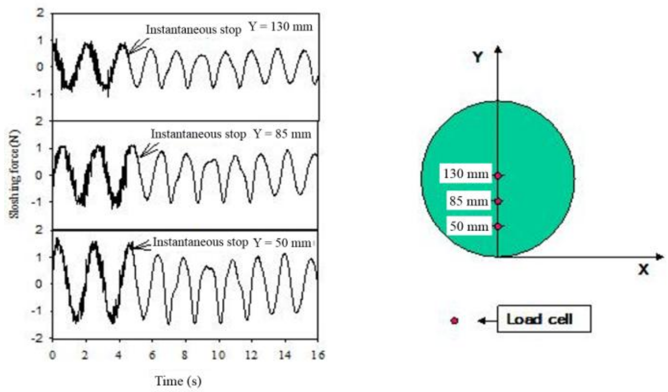


Fig.10. Variations of Sloshing Force Signals by Varying Load Cell Location

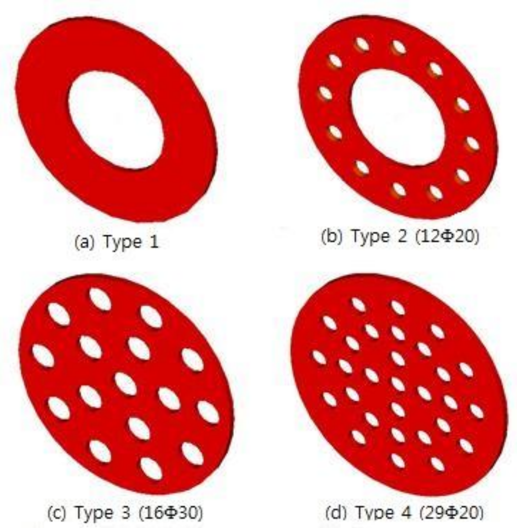
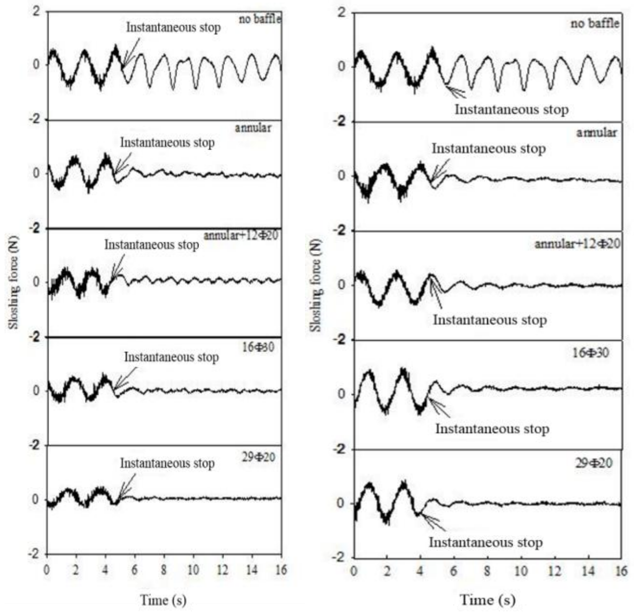


Fig.11. Type of Baffles for Sloshing Mitigation

Fig. 12 shows sloshing force signals measured by the load cell when tanks with one or two baffles were stopped instantaneously. Five types of experiments depending on the use and the type of baffle were considered: (1) no baffle, (2) Type 1 baffle, (3) Type 2 baffle, (4) Type 3 baffle, and (5) Type 4 baffle. The tank was set to be 50% full, the vibration amplitude was 40 mm, and the vibration frequency was 0.461 Hz of the first natural sloshing frequency. As shown in the figures, the presence of a baffle played a significant role in mitigating the sloshing force applied to the tank wall. In the case of (a), in which one baffle was used, the degree of sloshing mitigation varied depending on the type of the baffle being used; the Type 3 and 4 baffles mitigated the sloshing more effectively than Types 1 and 2. In particular, the Type 4 baffle reduced the sloshing force being applied to the tank wall to a greater extent than Type 3. In the case of (b), in which two baffles were used, the degree of sloshing mitigation was similar to the case of (a). However, when the tank was stopped instantaneously, the sloshing force applied to the tank wall decreased rapidly. In the same way as in the case of (a), the Type 3 and 4 baffles mitigated the sloshing more effectively than Types 1 and 2, while the Type 4 baffle reduced the sloshing force on the tank wall more than Type 3.



(a) Use of One Baffle **(b) Use of Two Baffles**

Fig.12. Sloshing Force Signals by Varying Use and Type of Baffles

Conclusion

To observe the sloshing phenomenon of the liquid storage tank, an experimental apparatus was manufactured in order to vibrate the tank at different vibration amplitude and vibration frequency. A digital video camera was used to record the sloshing of liquid. The mode shape and vibration frequency, which exhibited the maximum slope with bilateral symmetry, were determined as the mode shape and the natural frequency of sloshing. For a given amount of liquid, the natural sloshing frequency decreased as the vibration amplitude increased in the case of horizontal vibration in the longitudinal direction, but the natural sloshing frequency increased as the vibration amplitude increased in the case of horizontal vibration in the lateral direction. For a given vibration amplitude, the natural sloshing frequency increased as the amount of liquid in the tank increased, but the natural sloshing frequency decreased until the amount of liquid exceeded a certain level. On the other hand, the natural sloshing frequency decreased as the vibration amplitude increased, regardless of the amount of liquid. When the tank vibrated at the natural sloshing frequency was instantaneously stopped, the sloshing force at the tank wall increased due to a greater amount of liquid acting on the load cell. The use and type of baffles have a significant influence on the sloshing mitigation on the tank wall. Among the types of baffles with the same surface area, those with more holes of smaller diameters are more effective for the mitigation of the sloshing force.

Acknowledgements

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