International Journal of Recent Trends in Engineering, Vol. 1, No. 6, May 2009

Sloshing of Liquid in Partially Filled Container – An Experimental Study

P. Pal
Department of Civil Engineering, MNNIT Allahabad, India.
E-mail: prpal2k@gmail.com

***Abstract*–This paper deals with the experimental studies of sloshing of liquid in partially filled container subjected to external excitation. An experimental set-up is designed to study the behavior of liquid sloshing in partially filled prismatic container. At every instant of time, slosh amplitude is computed at specified location with the help of capacitance probe. The resulting slosh heights for various excitation frequencies and amplitudes are compared with the data available in literature. It is observed that the numerical results are closer to that obtained experimentally and little variations in the data are due to ineptness of the experimental set-up and the input parameters.**

***Index Terms*–sloshing, prismatic tank, capacitance probe, experimental set up.**

I. Introduction

Liquid in an arbitrary shaped container under external excitations, results in surface and bulk turbulence. The nature of such turbulence is quite complex due to several effects such as sloshing, pressure gradient etc. Amongst these, sloshing makes the liquid container more vulnerable to structural damages. Depending on the type of disturbance and container shape, the free liquid surface may experience different types of motion including simple planar, non-planar, rotational, irregular beating, symmetric, asymmetric, quasi-periodic and chaotic. However, the amplitude of slosh depends on the amplitude and frequency of the tank motion, liquid-fill depth, liquid properties and tank geometry. The resonance in the case of horizontal excitation occurs when the external forcing frequency is close to the natural frequency of the liquid. Hence liquid sloshing is a practical problem with regard to the safety of transportation systems, such as oil tankers on highways, liquid tank cars on railroads, oceangoing vessels with liquid cargo, propellant tank used in satellites and other spacecraft vehicles, and several others.

In the last few decades researchers have investigated sloshing of liquid numerically as well as experimentally. The special NASA monograph edited by Abramson [1] addressed the sloshing problems encountered in aerospace vehicles. The monograph contained the analytical and experimental studies of linear, nonlinear sloshing, damping of liquid motions, vertical excitations of tanks, interaction of liquid propellants and elastic structures, vehicle stability and control, liquid propellant behaviour at low and zero gravity, longitudinal oscillation of flight vehicles etc. Pal, Bhattacharyya and Sinha [2] conducted experimental studies on the sloshing response of liquid-filled containers. A three-dimensional finite element analysis was carried out for the numerical simulation of this problem [3]. The effects of sloshing were computed in the time domain using Newmark's time integration scheme. A simple experimental set up was designed and fabricated to conduct experiments for measuring some of the basic parameters of sloshing. A sensor device was developed to record the free-surface wave heights. Each wave height sensor was a capacitance probe that detected the change in level of liquid (water) precisely with no time lag. The sensors were used in conjunction with a signal-processing unit in which the capacitance values were transformed to a voltage signal between 0 V and 10 V. These wave height sensors simultaneously recorded the slosh wave height near the periphery of the container wall from predetermined locations to give the free-surface profiles of liquid at desired time steps. Biswal, Bhattacharyya and Sinha [4] presented the non-linear sloshing response of liquid in a two-dimensional rigid rectangular container with rigid baffles. A finite element technique was used to solve the nonlinear potential problems. Artificial smoothness of the shape function was not required as the authors had used rigridding technique on the free surface of the liquid. The authors solved the non-linear sloshing problems in a circular cylindrical container with annular baffle.

The focus of the present paper is to study the behavior of liquid sloshing in partially filled prismatic tank. The resulting slosh heights for various excitation frequencies and amplitudes are compared with the existing results.

II. Results and Discussions

The liquid sloshing in partially filled liquid containers is of concern to the researchers of aerospace, civil, nuclear field and several others. Understanding of any complex physical phenomenon like sloshing is enhanced by the use of experimental study to a great extent. Experimental studies help to check the validity of assumptions of the mathematical model and to employ the model effectively for treating container configurations on the basis of their design considerations. This section presents a detail description of the experimental set up and the measurement techniques used in the investigation.

The experimental studies were carried out by different researchers (Hunt and Priestley [5], Okamoto and kawahara [6] and Akyildiz and Unal [7-8]) to determine the liquid natural frequencies and the resulting slosh forces in liquid filled rigid containers. The experimental arrangement with appropriate instrumentation is set up to measure the slosh induced parameters of liquid-filled container and for capturing the response. Review of literature reveals a variety of experimental techniques that have been employed for carrying out experiments on oscillating tank models (laboratory scale models) for studying the sloshing phenomenon. In the present investigation an already fabricated shaker table having only unidirectional motion is used for the study. The driving mechanism of a lathe machine is a typical mechanical system which permits variations in the amplitude and frequency of oscillations. The table acting as a platform is supported on rollers with guided movement using spring attachments. A cam mechanism is used to transform the circular motion of the machine into a linear movement of the platform. The amplitude of the external excitation may be selected by adjusting the eccentricity of the connecting rod. Maximum possible amplitude in this shaking table is 0.06 m. A prismatic tank model of size 0.50 m in width, 0.35 m in breadth and 0.40 m in height, made of perspex, is fixed to the platform through a fixing arrangement. These dimensions are considered similar to ones, available in literature [1], for comparison. It may be noted that the transparent prismatic tank partially filled with water used in the present experiment is primarily aimed at visual observation of the sloshing modes. The photograph of the experimental arrangement and the instrumentation are shown in Fig. 1.

The wave height measuring probes along with the amplifier developed in house are used for the measurement of slosh amplitudes. Voltage signal from the probes are amplified using the amplifier system and the amplified signals are scanned and recorded using a 16-channel HP Bench link data-logger system. All data are stored in a personal computer of P4 series with 512 MB RAM.

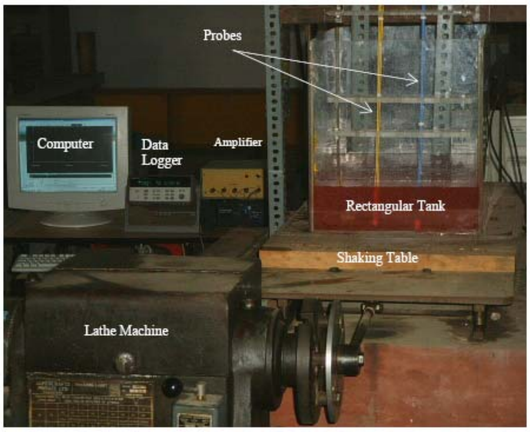

Figure 1. Experimental arrangements and the instrumentations

A. Measurement of Slosh Displacements

Sloshing height is measured using the capacitance probe at different locations into the container subjected to different excitations. Fig. 2 shows the position of two probes in different positions in the prismatic tank during experiment and the photograph of the typical arrangement of these probes are shown in Fig. 3. The slosh amplitudes are measured and presented in the form of amplitude to tank width ratio (ζ/L).

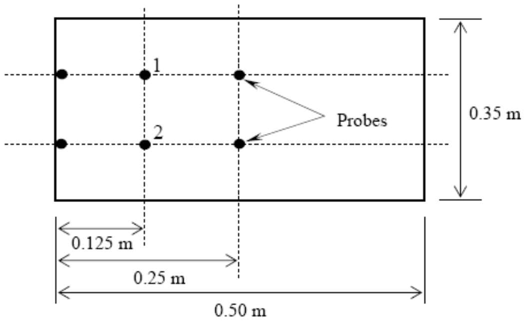

Figure 2. Position of probes – A plan view

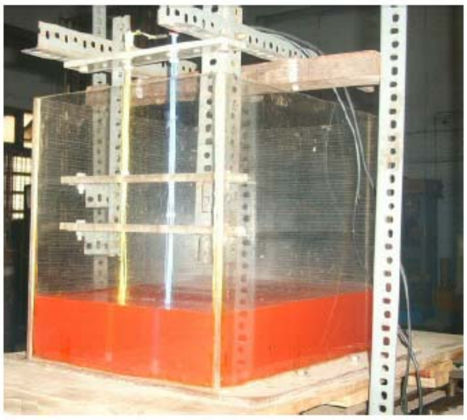

Figure 3. Typical arrangement of sensors

Fig. 4 shows the sloshing height at the probe position 1 and 2 in container for depth ratio h_L/H equal to 0.25, subjected to sinusoidal horizontal base excitation with 0.0025 m amplitude and a frequency of 5.236 rad/sec. Fig. 5 shows the sloshing height at the probe position 1 and 2 for the same amplitude and h_L/H ratio, but with the excitation frequency of 7.854 rad/sec. The electrical signals are continuously recorded with the help of a 16-channel data acquisition system. Numerical solution has been carried out considering the same input data [9]. Comparison between the present experimental and numerical results of the free surface slosh amplitude near the container wall is shown in Figs. 4 and 5.

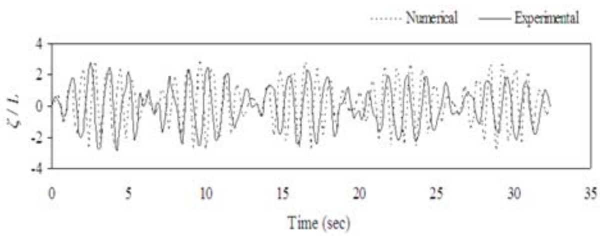

Figure 4. Comparison of experimental and numerical results of sloshing amplitude near the wall of a prismatic tank

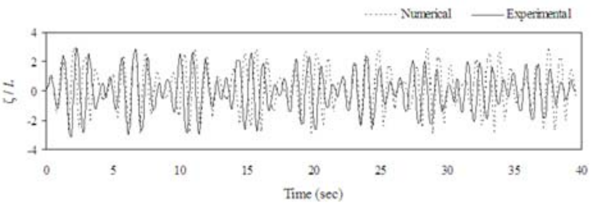

Figure 5. Comparison of experimental and numerical results of sloshing amplitude near the wall of a prismatic tank

It is observed that after each cycle of oscillation, the movement stalls for a small time and again liquid starts oscillating. These are caused due to dissipation of energy. It is noticed that the computed sloshing amplitudes are out of phase from the experimental data at certain times. However, the pattern of movement stalls is trivially matched. These results may be regarded as satisfactory considering various limitations and approximations made during the experimental measurements. As the tank oscillates, different sloshing waves are created depending on the liquid depth and external excitation. These are presented in parametric study.

B. Measurement of Slosh Frequencies

Liquid sloshing is a result of the motion of partially filled tank. As the tank moves, it supplies energy to sustain the liquid motion. If the frequency of the tank motion is close to one of the natural frequencies of the liquid, large sloshing amplitude occurs. For a given prismatic tank, the natural frequencies of the liquid depending on the fill depth are obtained from the expression [1] as given below:

$$\omega_n^2 = \left(\frac{g\xi}{4\pi}\right)\tanh\left(\pi h_l \xi\right) \quad and \quad \xi = \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \qquad (1)$$

where, m or n is the number of half waves in the X -or- Z direction, h_l is the liquid depth, a and b are the lengths of the sides of the container. The general technique to measure the liquid natural frequency is to oscillate the tank at low amplitude and then stop the oscillation and record the frequency at which the undistorted wave shape reaches the maximum amplitude without rotation. The experimentally measured values of the first natural sloshing frequency for the test model tank for different depths of liquid are presented in Table 1. The results are compared with the reported results published by Abramson [1]. It is observed that the experimental results are closer to the ones indicated in literature. These results may be regarded as satisfactory considering various limitations and approximations made during the experimental measurements.

TABLE I.

SLOSH FREQUENCIES, F_N (HZ) OF LIQUID IN A PRISMATIC CONTAINER

Depth ratio, (h_l/H)	Abramson [1], ω_n	Experimental values, ω_{ns}
0.175	4.959	4.9587
0.200	-	5.1491
0.225	5.236	5.2346
0.250	-	5.3267

C. Parametric Study on Slosh Frequency

The selected tank is considered for the present experimental investigation. The capacitance probe is used to measure the variation of slosh amplitude at different locations inside the tank. The different probe positions into the container are –0.5L, –0.25L, 0, +0.25L, and +0.5L, respectively (Fig. 2). Centerline of the tank is taken as reference line. Tank is examined for different depths of liquid. A few cases are presented here to observe the variation of non-dimensional slosh amplitude with the change in depth ratio, amplitude and frequency of applied acceleration.

Where, depth ratio (h_L/H) = Depth of liquid into the tank / Height of the tank

Non-dimensional slosh amplitude (ζ/L) = Sloshing height at a particular point / Width of the tank

C1. Variation of Slosh Amplitude Due to Change in Depth Ratio

The slosh amplitude is measured for different depths of liquid (water) into the selected tank. The non-dimensional slosh amplitude is plotted with the variation of depth ratio and is shown in Fig. 6 for different external amplitude without changing the frequency of 5.236 rad/sec. It is observed that as the applied amplitude increases, slosh amplitude increases. Fig. 7 shows the plot of non-dimensional slosh amplitude with various depth ratios for different excitation frequency without changing the external amplitude of 0.005 m. It is observed that as the excitation frequency increases, slosh amplitude decreases. Further, increase in the liquid depth causes decrease in slosh amplitude. However, for a particular value of depth ratio (0.15), it is showing a local peak value. This may be due to the closeness of external frequency to one of the fundamental slosh frequencies of the container liquid. The slosh amplitude for different liquid depths are plotted in Fig. 8 subjected to particular applied amplitude of 0.005m with varying applied frequencies. It is observed that slosh amplitude follows sinusoidal pattern because of sinusoidal nature of applied external excitation.

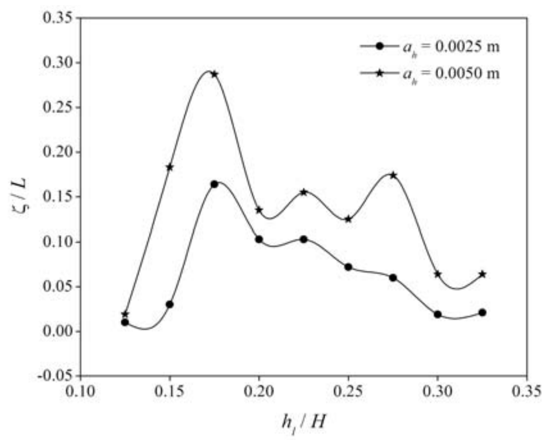

Figure 6. Non-dimensional slosh height with various liquid depths for different applied amplitudes without changing the applied frequency

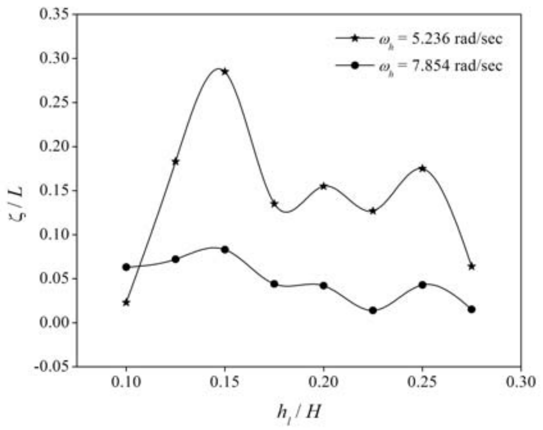

Figure 7. Non-dimensional slosh height with various liquid depths for different applied frequencies without changing the applied amplitude

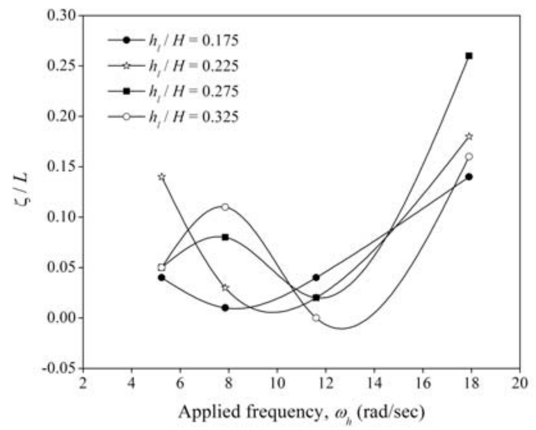

Figure 8. Variation of non-dimensional slosh height with applied frequency for different applied amplitudes

C2. Variation of Slosh Amplitude Due to Change in Excitation

The selected tank model is examined for a particular depth of liquid to observe the change in sloshing amplitude with varying applied frequencies and amplitudes. The depth of liquid is 0.13 m. The non-dimensional slosh amplitude at different applied amplitudes with the change in applied frequencies is plotted in Fig. 9. It is observed that the slosh amplitude follows sinusoidal pattern, i.e., slosh amplitude increases initially with the increase of applied frequency and thereafter it decreases and again with the increase in external frequency slosh amplitude increases. This is because of sinusoidal nature of applied external excitation on the liquid-filled container. The non-dimensional slosh amplitudes are plotted for a constant applied frequency of 5.236 rad/sec with varying the applied amplitudes, which is shown in Fig. 10. It is observed that the slosh amplitude increases with the increase in applied amplitude. However, slosh amplitude decreases with the increase in liquid depth. The selected tank is examined after sudden release of external excitation, which is shown in Fig. 11. The depth of liquid is 0.09 m, applied frequency is 5.236 rad/sec and applied amplitude is 0.005 m. It is observed that the slosh amplitude decreases exponentially with time.

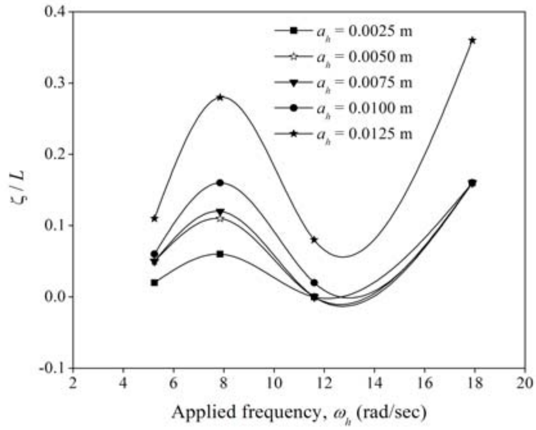

Figure 9. Variation of non-dimensional slosh height with applied frequency for different liquid depths

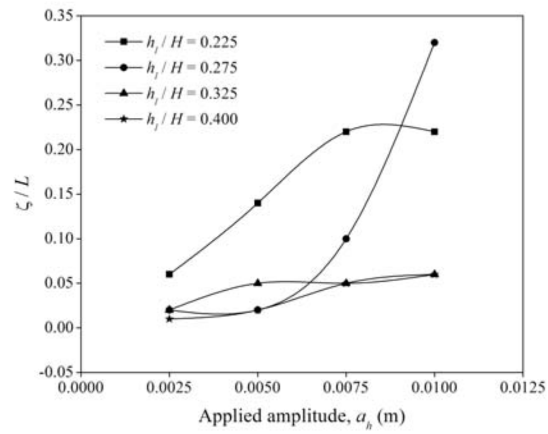

Figure 10. Variation of non-dimensional slosh height with applied amplitude for different liquid depths

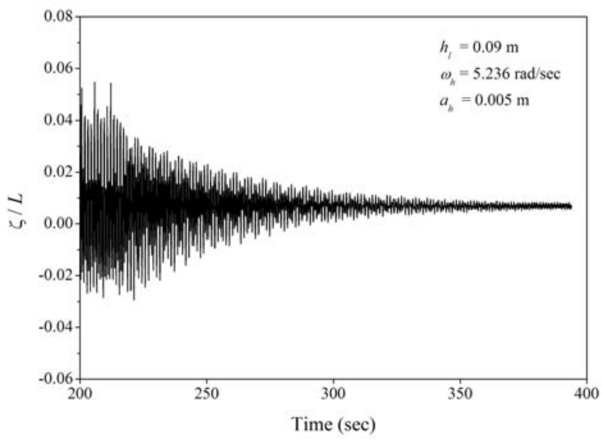

Figure 11. Non-dimensional sloshing amplitude after offing the external excitation

CONCLUSIONS

The experimental studies of sloshing of liquid in partially filled container are presented in this paper. The computed results are compared with the published results, and good agreement is found. It can be noted that the slosh characteristics are strongly influenced by the tank geometry, depth of liquid, and the amplitude and frequency of external excitation. For a particular depth of liquid in container subjected to sinusoidal base excitation, it is observed that after each cycle of oscillation, the liquid movement stalls for a small time and again liquid starts oscillating due to dissipation of energy.

The numerical results are not matching exactly with those obtained experimentally and the variations in the data may be due to in adequacies of the experimental set up and the input parameters. More work is needed so that the measurement technique can be extended to any arbitrary tank geometry.

NOTATION

The following symbols are used in this paper:

L = Width of the tank (m)
B = Breadth of the tank (m)
H = Height of the tank (m)
h_l = Depth of liquid into the tank (m)
a_h = External applied amplitude (m)
ω_h = External applied frequency (rad/s)
ζ = Sloshing amplitude (m)
ω = Sloshing frequency (numerical, rad/sec)
ω_{ns} = Sloshing frequency (experimental, rad/s)

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