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Experimental and Numerical Modal Analysis of Sloshing in a Rectangular Tank

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***Abstract*— The work is mainly concerned with the design of a shaker table to estimate the slosh frequency and to study its effect on slosh modes. It includes numerical modeling of the rectangular tank in ANSYS and experimental modeling with the combination of test rig and LABVIEW software. The slosh frequency obtained experimentally were compared with those of numerically obtained values**

***Keywords*— Sloshing,Slosh Frequency,Slosh Modes**

I. INTRODUCTION

In fluid dynamics, slosh refers to the movement of liquid inside another object. Sloshing is defined as the periodic motion of the free surface of a liquid in a partially filled container or tank. The liquid must have a free surface to constitute a slosh dynamics problem, where the dynamics of the liquid can interact with the container to alter the system dynamics significantly. In many engineering problems the dynamic interaction between fluid and structure is a significant concern. These problems include diverse systems such as off-shore and submerged structures, biomechanical systems, aircraft, suspension bridges, storage tanks. The basic problem of liquid sloshing involves the estimation of slosh frequencies and displacement of the free liquid surface. These parameters have a direct effect on the dynamic stability and performance of moving containers. Liquid sloshing in a transport system is associated with various engineering problems such as transporting vehicle on highways, sloshing of liquid cargo in LNG container ship and the motion of liquid fuel in aircraft and spacecraft. Therefore, an understanding of the sloshing mechanism is very important in engineering applications.

If the liquid is allowed to slosh freely, it will produce force that results in additional vehicle accelerations. In launch vehicles/spacecraft these accelerations are sensed and responded by control and guidance system, which form a closed loop leading to instability. Slosh induced stability leads to structural failure, premature engine shutdown and inability of spacecraft to achieve upper stage engine start through propellant loss at the drain port as well as through the tank vent system. Even in a low or non-zero environment, where the slosh frequencies are very low and the torques exerted on the vehicles may not be great, slosh occurs due to long-term liquid motions which give rise to amplitudes thus resulting in failure. Several booster vehicles have been prone to failures due to the absence of inadequate slosh suppression devices. For example, there was premature engine shut off during the first Saturn flight due to the rotary slosh which was induced by the roll-control loop of the guidance system with coupling and the improper covering of propellant drain line.

Aboveground steel storage tanks are widely utilized in industrial areas such as oil refineries, petro-chemical complexes, oil depots and assurance of these infrastructure facilities in high seismic areas is a very important engineering consideration. High amplitude fluid sloshing is one of the widespread causes of water and oil storage tanks during strong earthquakes addressed as an important failure mode. The additional force generated during sloshing had got a great impact on the wall and roof of the tanks. Sloshing in a liquid tank results in instability or structural damage, so in order to restrain liquid sloshing and prevent tank damage inner structures are more often used.

Panigrahy P.K, Saha U.K and Maity.D [4] have carried a series of experiments in a developed liquid sloshing setup to estimate the pressure developed on the tank walls and the free surface displacement of water from the mean static level. An experimental setup similar to that is designed so that it can be used to determine the slosh frequency and its impact on sloshing.The rectangular tank attached to a shaker table can be moved to and fro by a micro-controller arrangement driven by a hybrid servo motor.

The entire work is divided into two sections- design of shaker table and modal analysis of the tank. The tank motion is a pure surge i.e. translation in the X-direction only.

II. THE TEST RIG

The test rig which was designed and developed to study sloshing effect on the tank is shown in Fig. 1. It consists of two rails mounted on an aluminium base plate and a recirculating ball screw in the midway between these two rails. One end of the ball screw is connected to motor while the other end is blocked to restrict motion. The two rails are placed at an equal distance from the edge of the base plate. A hybrid servo motor which has been programmed induces to and fro motion of the ball screw. Chromium plate is mounted on the top of two rails and is also in contact with the ball screw. Water tank made of acrylic glass is clamped to the top of the chromium plate. The aluminium base is provided with dampers to avoid vibrations. Laser Displacement sensor and accelerometer are used for the measurement of displacement and acceleration respectively. This whole assembly is then mounted on to large base with dampers provided in between to avoid vibrations.

Fig. 1.Experimental Setup

III. EXPERIMENTAL MODELING USING LABVIEW SOFTWARE

The experimental setup for conducting slosh experiment is shown in Fig. 1. The setup consists of tank made up of acrylic glass, hybrid servo motor, laser displacement sensor, Arduino micro-controller, data acquisition card, encoder, external power supply, bread board and liquid (water).

The water tank mounted on shaker table has got movement only in length (X direction), so it's better to place the laser displacement sensor along horizontal (length) direction. A hybrid servo motor gives to and fro motion of the tank. Arduino micro-controller is used to control the pulse and direction of motion of servo motor. Arduino Software contains a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions and a series of menus. It connects to the Arduino and Genuino hardware to upload programs and communicate with them. Displacement sensor is connected to the data acquisition card which in turn is connected to the laptop via cable. The software used for analysis is LABVIEW. The light beam from the Laser displacement sensor is projected perpendicularly onto the water surface in the tank and the diffuse light that is reflected back is received for a wide measurement area. Displacement sensor is connected to Data Acquisition Card which in turn is connected to laptop via cable. It gives the displacement-time relationship and using Fast Fourier Transform (FFT), the time domain in power spectrum is converted to our desired frequency domain. Displacement sensor gives the amplitude of sinusoidal motion but the main concern is in finding out the frequency.

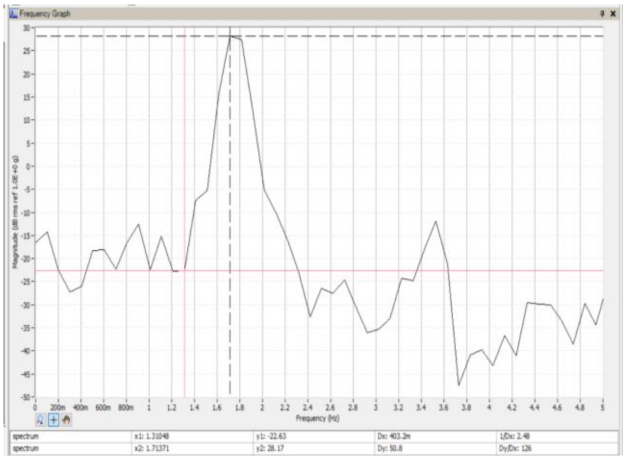

Fig. 2. Slosh frequency corresponding to 1st mode

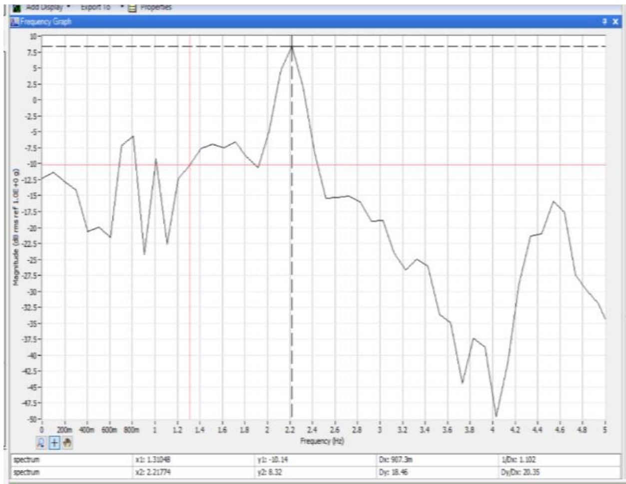

Fig. 3. Slosh frequency corresponding to 3rd mode

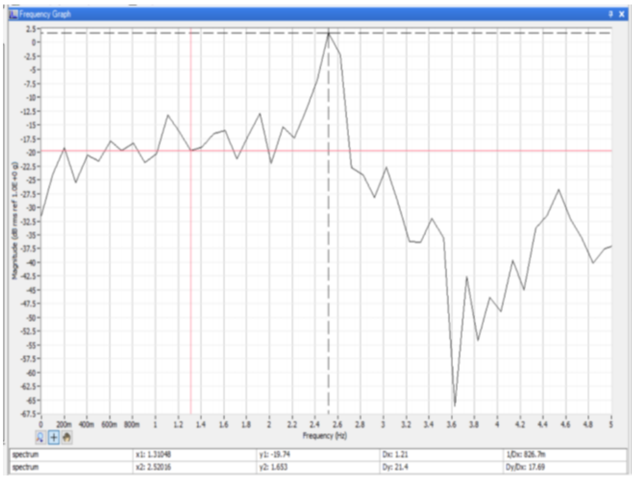

Fig. 4. Slosh frequency corresponding to 4th mode

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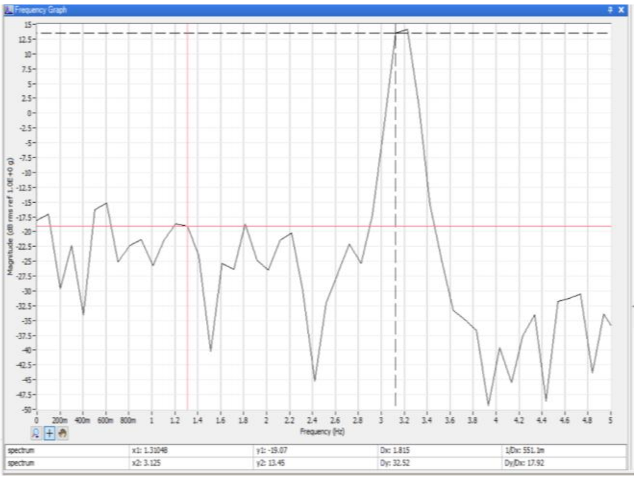

Fig. 5. Slosh frequency corresponding to 6th mode

Fig. 2 to 5 shows the frequency values corresponding to their respective modes. The frequency graph obtained in LABVIEW software is a logarithmic scale but not linear. The slosh frequency values are very much smaller and the graph obtained cannot highlight the smaller peak and thereby frequency values. For this purpose, the graph has been converted into logarithmic scale and increased the sampling rate to get a high resolution graph. The smaller peaks in the graph correspond to particles that come along the path of sensor and the highest peak stands for the slosh frequency. An Infinite Impulse Filter (IIR) is used to cut off the higher frequencies as we are interested in only lower frequency range i.e. slosh frequency. The sharp peak directly gives the frequency value whereas the slope of the frequency graph is due to the signal leakage and the frequency value is taken by averaging both the end points of the folded peak.

IV. NUMERICAL MODELING USING LABVIEW SOFTWARE

Modal analysis is a technique used to determine water tank vibration characteristics such as slosh frequencies, mode shapes and mode participation factors. This is the most fundamental of all the dynamic analysis types. The various elements and the parameters used in ANSYS 16 for the modal are, Cross-section of the tank: Length (L) = 0.24 m, Breadth (B) = 0.20 m, Height (H) = 0.24 m, Thickness (T) = 0.006 m, Material of tank = Acrylic glass, Young's modulus (E) = 3.2 GPa, Density of tank = 1190 kg/m^3, Density of water = 1000 kg/m^3, poison's ratio (μ) = 0.35.

The motion of the tank can be specified by three translations and three rotations about the centre of mass of the liquid. The combined effect of translations and rotations of water is quite important as the water present in the tank behaves slightly compressible. The slosh frequency of water in tank is shown in Fig. 5 and the mode shapes irrespective of their slosh frequencies is shown in Fig. 7 to 10. Except the second mode shape which is observed along Y-direction, all other mode shape propagates along X-direction which is the main concern in the thesis work.

***** INDEX OF DATA SETS ON RESULTS FILE *****

SET	TIME/FREQ	LOAD STEP	SUBSTEP	CUMULATIVE
1	0.68836E-06	1	1	1
2	1.7697	1	2	2
3	1.9600	1	3	3
4	2.2522	1	4	4
5	2.5568	1	5	5
6	2.7627	1	6	6
7	2.8052	1	7	7
8	2.9203	1	8	8
9	3.1439	1	9	9
10	3.2046	1	10	10
11	3.2633	1	11	11
12	3.4538	1	12	12
13	3.5188	1	13	13
14	3.5635	1	14	14
15	3.6486	1	15	15

Fig. 6. Frequency Results of Water Tank with Slosh

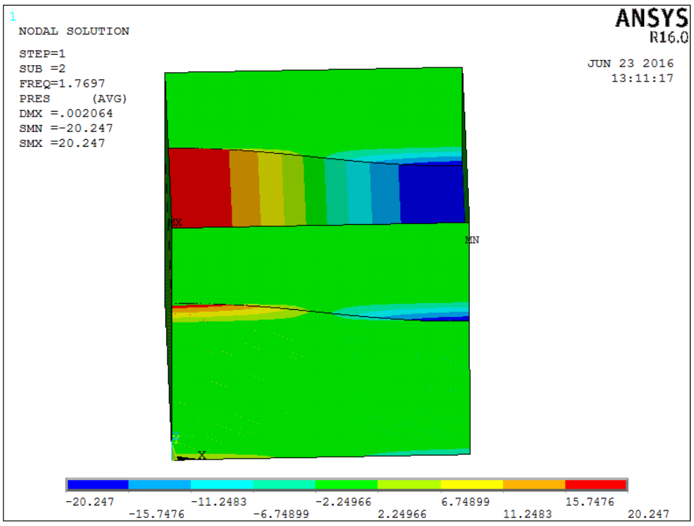

Fig. 7. Mode shape at slosh frequency 1.7697 Hz

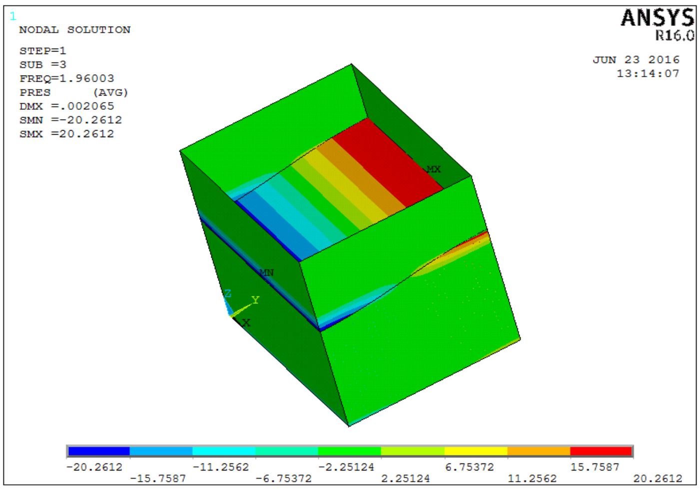

Fig. 8. Mode shape at slosh frequency 1.96 Hz

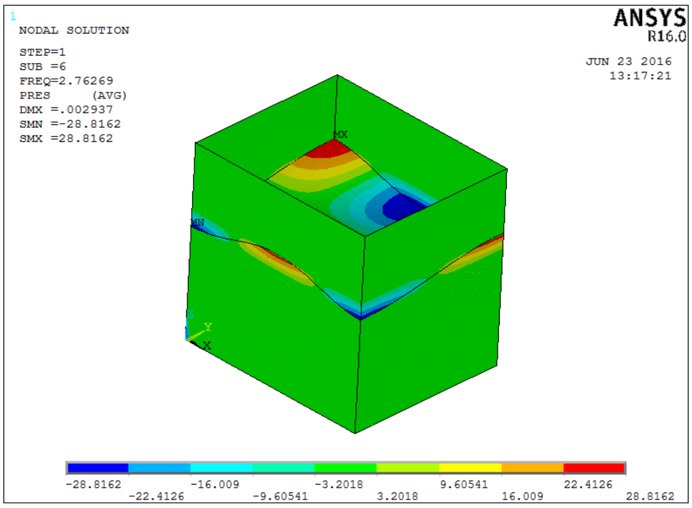

Fig. 9. Mode shape at slosh frequency 2.763 Hz

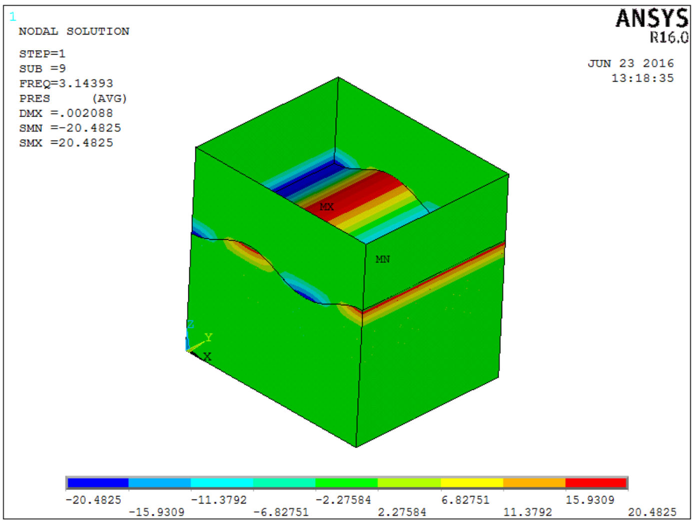

Fig. 10. Mode shape at slosh frequency 3.144 Hz

V. RESULTS AND DISCUSSION

TABLE.I. FREQUENCY OBTAINED FROM EXPERIMENTAL AND NUMERICAL MODAL ANALYSIS

Mode	Experimental modal analysis (Hz)	Numerical modal analysis (Hz)
1	1.7600	1.7697
2	_	1.9600
3	2.217	2.2522
4	2.57	2.5568
5	2.78	2.7627
6	3.17	3.1439

Comparison of experimental modal analysis obtained from LABIEW software with those of numerical modal analysis values from ANSYS 16 is shown in Table.1. It is found that the first mode value differ by -0.55%, third mode differ by -1.5%, fourth mode by 0.5%, fifth mode by 0.6% and sixth mode by 0.8%. Second mode propagates along y-direction (breadth) is not taken into consideration as tank motion is pure surge having translation in the x-direction only. The variation in the values is due to the type of disturbance and tank shape, so that the free liquid surface will experience different motions like simple planer, non-planer, rotational, irregular beating.

VI. CONCLUSIONS

A shaker table was designed and developed which can be used for any type of vibration test in the lower frequency range (0-20Hz). Prototype of automobiles, buildings, engines and other industrial equipments prone to vibration can be tested using this shaker table. Modal analysis of the rectangle tank provides us with the information of how the slosh modes propagate through the water medium corresponding to their respective slosh frequency. Comparison of both experimental and numerical values provides with the information that error difference lies in the range -0.5% to 0.8%.

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