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Design and Fabrication of 6 Degrees of Freedom Sloshing Setup using Ship as a Test Rig

Waqar Shoukat Awan[1], Dr. Ajmal Shah[2], Dr. Zaheer Asghar[3]
[1]Department of Mechanical Engineering PIEAS, Centre for Mathematical Sciences PIEAS
[2]Department of Mechanical Engineering PIEAS, Centre for Mathematical Sciences PIEAS
[3]Department of Physics & Applied mathematics PIEAS, Centre for Mathematical Sciences PIEAS
[1]msme2311@pieas.edu.pk/waqar.awan.jspsc@gmail.com
[2]ajmal@pieas.edu.pk
[3] zaheerasghar@pieas.edu.pk

Abstract

The focus of this study is on design and development of six degrees of freedom sloshing test apparatus. This objective was achieved by using ship as a test rig. A plexi-glass tank is mounted over the ship. This ship with mounted tank floats in another large plexi-glass container of water, placed over the table. Waves were generated in large tank using wave generator. Wave generator is a device operated using computer code. This wave generator is fixed at one end of the large container. Wave generator produces sinusoidal waves that collide with the ship causing sloshing is the mounted tank. A gyro sensor is fixed over the mounted tank that records components of acceleration in three directions and three angles i.e. x, y, z, roll, pitch and yaw respectively. The components of three accelerations show forces acting on mounted tank in three directions. This vector force had combined effect of sloshing force as well as force due to water waves that collided with ship. The graphs of roll and pitch motion showed somewhat oscillatory behavior while the graph of yaw was random which is quite realistic. The maximum acceleration of 1.9 m/s^2 is obtained in x direction, 2.9 m/s^2 is obtained in y direction and 1.7 m/s^2 is obtained in z direction. The behavior of forces was aligned with acceleration components in respective directions.

Keywords: sloshing, ship, wave generator, sinusoidal wave

Introduction

Liquid cargo trade is one of the largest trademarks in the world. Almost all the liquids of daily, commercial, and industrial use are transferred from one place to another using liquid tankers. Diversity of fluids transferred via tankers is very large. It includes eatables, daily usage materials, toxins, fire-hazardous equipment and many more. This study targets the real time situation faced by cargo ships carrying LNG. When waves collide, LNG sloshes and this phenomenon exerts forces on ship. Fluid transportation in ships and tankers is not only common on earth, but it is also popular in space vehicles. Common problems faced during transportation of liquids and gases are spillage, explosions, and accidents due to instability of vehicle carrying a liquid for transportation. Godderidge et al. have verified and validated the use of CFX and ANSYS FLUENT to simulate lateral sloshing. They had tried to make a consensus over the use of many CFD options available. They had used a 1.2 m long, and 0.6 m high tank filled with 60% liquid and excited with 95% of the natural frequency with maximum displacement not more than 1.25% of the total length of the tank. They had given recommendations over many CFD factors in detail. They had also tried to describe physics of sloshing. They had found that compressible-incompressible model is 20% computationally cheaper for air-water as compared to fully compressible model [1]. Lateral sloshing simulation has been verified and corrected by Godderidge et al. by using CFX. To perform the experiment, a tank with dimensions of (1.2 m × 0.6 m) has been used and it has been excited to 95% of the natural frequency with an amplitude of 1.25% of total tank length. V. Singal et al. encompassed the CFD analysis of the kerosene fuel tank with and without baffles and reported a significantly improved damping in the first case. They had used ANSYS FLUENT for simulation purposes. They had further hinted that the incorporation of the baffles would decrease the overall sloshing thereby ensuring the continuous supply to the engine [2]. Bouabidi studied time step size effect on the liquid sloshing phenomena in rectangular tank [3]. P. K. Panigarh has experimentally studied sloshing due to horizontal excitation in baffled tanks and found out that vertical baffles help reduce sloshing [4]. Faltinsen and Timokha have presented a modal theory to analyze the non-linear sloshing phenomenon in an incompressible and irrotational fluid stored in a rectangular tank 7 [5]. A tank with an infinite roof height having no wave reflection was assumed in this study. Non-linear ODEs formed the basis of purposed theory. This theory incorporated polynomial with fifth-order non-linearity considering extremely small fluid-zone motion relative to filling depth and tank width. Nicolici and Bilegan have published a comparative study of four different fluid-solid interface coupling models for vertically supported cylindrical tanks [6]. The first model included two-way FSI coupling, the second model included one-way FSI coupling, the third corresponded to lumped mass approach, and Distributed fluid mass approach was considered in the last model. Khouf et al. have reported a comprehensive study on the response of flexible tanks subjected to violent sloshing [7]. In this study, a staggering fluid-solid coupling approach was used to investigate the impact of large amplitude sloshing on structural integrity. Kim et al. have reported a numerical study on the sloshing phenomenon coupled with ship motion [8]. The impulsive response function was used to model the linear slosh phenomenon, while the finite element method was used to simulate nonlinear sloshing flows. Liu et al. have conducted a numerical study of liquid sloshing coupled with the parametric rolling of a ship [9]. A scaled model of ONR Tumblehome containing a partially filled water tank was considered in this study. For numerical study, an unsteady RANS solver was used to study the sloshing dynamics of the system with different fill depths and ship speeds. Joshi et al. have studied the sloshing phenomenon in a chamfered tank having different filling depths subjected to various sway excitation frequencies and analyzed the effect of vertical baffles, placed at the bottom of the tank, on the sloshing parameters [10]. This study concludes that the baffles installation in the tank substantially decreases the sloshing impact pressure as well as structural instability of the container. Gándara et al. have reported a numerical as well as an experimental study of the sloshing phenomenon in a stepped rectangular tank [11]. This study incorporated a fixed mesh ALE approach to evaluate structural loads due to sloshing. The present study aims to build an indigenous slosh force measuring apparatus using ship as a test rig.

Materials and Methods

Design and Analysis of ship-tank subassembly

The ship is made up of commercially available 10 mm thick PVC foam board and it is waterproofed using commercially available silicon sealant. The detailed analysis of ship is done using the following equations.

$$V_{ship} = \left(xz + \frac{xa}{2}\right)(y - t) \tag{1}$$

$$V_{solid\ ship} = \left(xz + \frac{xa}{2}\right)t + 2(zyt) + (x+2t)yt + ayt + \frac{xyt}{2} + yt^2 + other\ volume \quad (2)$$

$$W_{ship} = \rho_{ship\ material}(V_{solid\ ship})(g) \quad (3)$$

The top view of ship is given in Figure 1. Let the volume of hollow space in ship be V_{ship}, volume of solid material of ship is $V_{solid\ ship}$, weight of the ship is W_{ship}, volume of tank mounted on ship is V_{tank}, buoyant force is F_b, a, x, y, z be the linear dimensions. Here 't' means the thickness which is 10 mm, 'x' is 400 mm, 'z' is 450 mm, and 'a' is 100 mm while $\rho_{ship\ material}$ is the density of ship material which is 600 $\mathrm{kg/m^3}$. The 'other volume' shows solid volume of supporting structures for tank. The stability analysis graph of ship-tank subassembly is given in Figure 3.

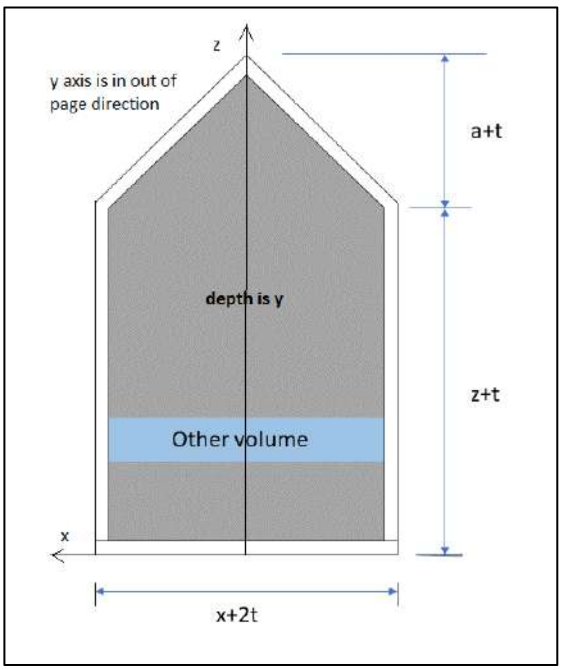

Figure 1 Top view of ship

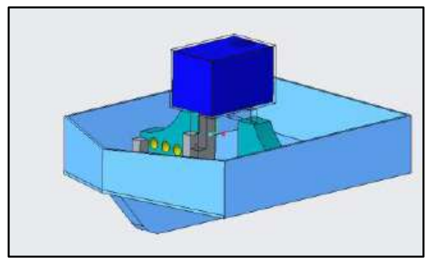

Figure 2 Ship with sloshing tank (ship-tank subassembly)

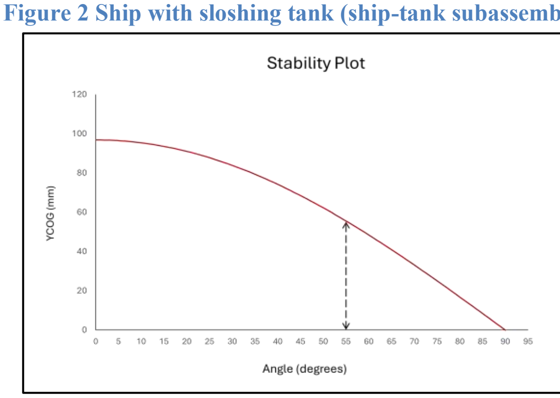

Figure 3 Stability curve of ship-tank subassembly with reference to roll motion

From the graph, it is not directly clear what is the limiting angle of stability. However, it can be observed that ship sub assembly will get unstable when the imaginary line passing from center of gravity will get out of the base of ship. That angle shall be the limiting value of stability. This was the case for solid mechanics but in case of floating structure, restoring moments will act upon the ship since its metacentric height is positive thus increasing its stability angle than 55 degrees. The plot of center of gravity and angle at which the imaginary line passing from center of gravity will get out of the base of ship is shown. The tank is made up of commercially available plexi-glass as shown in Figure 4.

$$\text{Mass of tank} = V_{st}(\rho_{tank\ material}) \quad (4)$$

$$\text{Total weight over ship} = \rho_{water}(V_{tank})(g) + V_{st}(\rho_{tank\ material})(g) \quad (5)$$

$$F_b = \rho_{water}(V_{tank})(g) + V_{st}(\rho_{tank\ material})(g) + W_{ship} \quad (6)$$

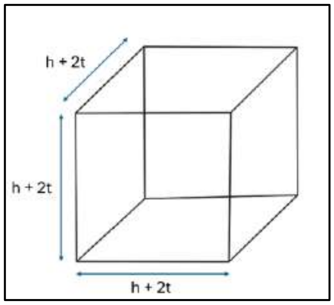

Figure 4 Tank diagram. Here 'h' is 100mm and 't' is 3 mm

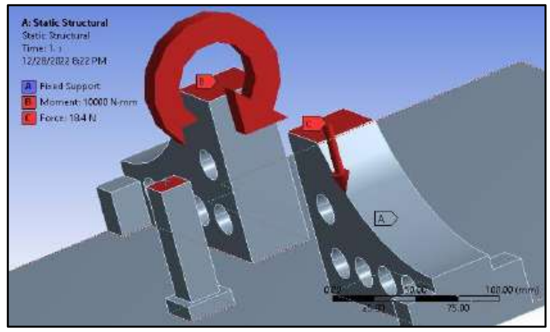

Figure 5 Force and moments acting on ship

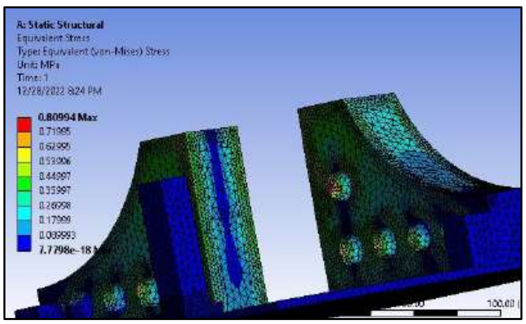

Figure 6 Stress analysis of ship

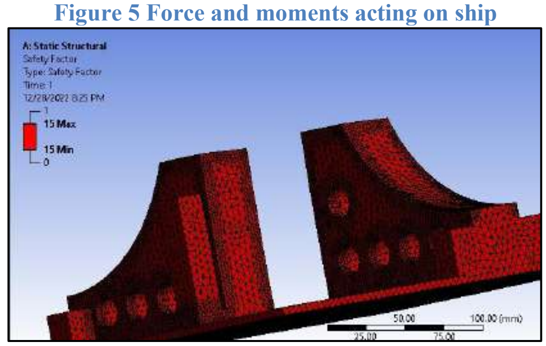

Figure 7 Factor of safety of ship

$$F_b = \left((x + 2t)(z + t) + \frac{1}{2}(x + 2t)(a)\right)(\zeta)(\rho_{water})(g) \quad (7)$$

V_{st} is the solid volume of plexi-glass, V_{tank} is the internal volume of tank, $\rho_{tank\ material}$ is the density of plexi-glass which is 1180 kg/m^3, and ρ_{water} is water density at room temperature which is 1000 kg/m^3. F_b is the buoyant force acting on ship and ζ is the depth of ship in water. Equating (6) and (7) give us the value of ζ which comes out to be 30 mm. The force and moment being primarily applied on ship is shown is Figure 5.The mesh independent results using tetrahedral mesh algorithm are reported where Figure 6 shows equivalent von-Mises stress acting on ship with its maximum value of 0.8 MPa and Figure 7 shows safety factor reported based on endurance limit with its maximum value more than 15 everywhere. The design is extremely safe and has been done on basis of fatigue criteria. The manufactured ship is shown in Figure 8 and tank is shown in Figure 9.

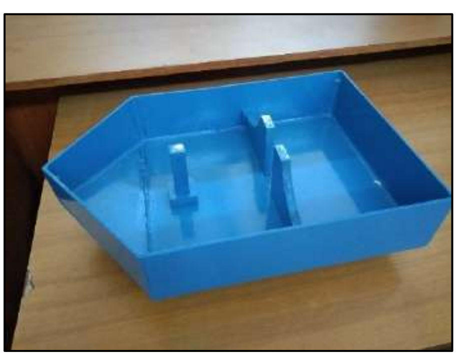

Figure 8 Ship fabrication completed in PIEAS

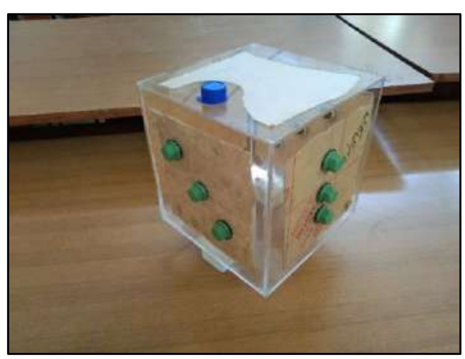

Figure 9 Tank Fabrication completed in PIEAS

Design and Analysis of Table

A table with wooden top and structural steel stand having elastic modulus of 210 GPa is used to place large water container on which ship-tank subassembly floats.

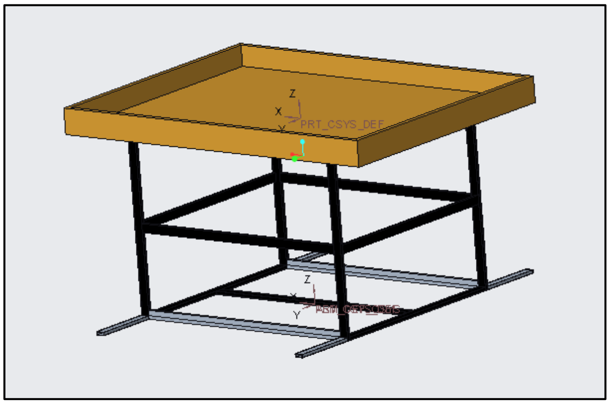

Figure 10 CAD model of table

Figure 11 Manufactured table in PIEAS

$$W = W_{wood} + W_{container} + W_{water} + W_{ship} + W_{tank} \quad (8)$$

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \quad (9)$$

$$\mathrm{I} = \frac{1}{12}(\mathrm{b_1 h_1^3} - \mathrm{b_2 h_2^3}) = \frac{1}{12}(19.05^4 - 18.05^4) = 2.12 \times 10^{-9}\, m^4 \quad (10)$$

Where W is the total weight on table stand, W_{wood} is weight of wooden top, $W_{container}$ is the weight of large cuboid container, W_{water} is weight of 60% fill level water in large cuboid container, W_{ship} is weight of ship and W_{tank} is weight of 100% water filled tank. The W comes out to be 15062 N. The weight acting on one leg is 3465 N. The critical load for buckling is calculated using (9) and comes out to be 76283 N. The safety factor on buckling basis comes out to be 76283/3465 = 20. This shows design is very safe with respect to buckling.

Design and Analysis of Wave Generator

The wave generator can produce sinusoidal waves of different frequencies and amplitudes by changing RPM and number of rotations of motors. These waves will collide with the ship and cause it to move. This will introduce sloshing in the water tank mounted on the ship. It consists of V slot gantry system and its control system. A V-slot gantry system is used to convert rotary motion of motor to translational motion. Its plank motion produces waves. Gantry system includes the aluminum Extrusion, Gantry Plate, Lead Screw, Lead Screw Nut, V- Plate, Wheels, Eccentric & non-eccentric spacers. Its CAD model is shown in Figure 12.

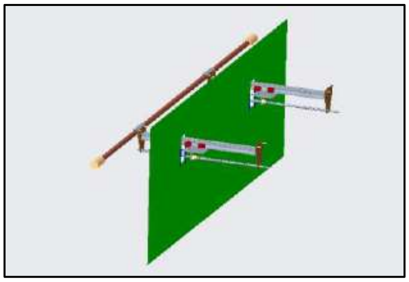

Figure 12 CAD model of wave generator

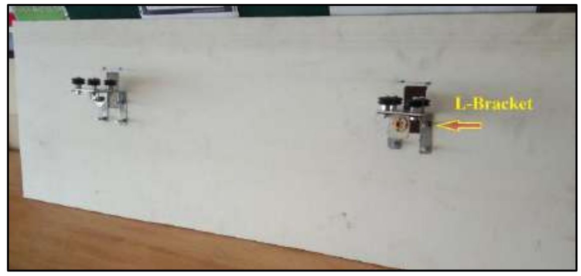

Figure 13 Manufactured wave generator in PIEAS

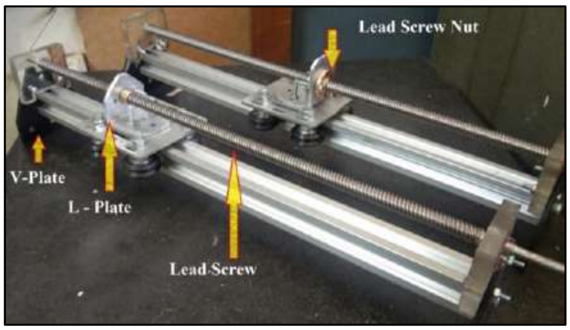

Figure 14 V-slot gantry system manufactured in PIEAS

Figure 15 Complete sloshing apparatus manufactured in PIEAS

Ship Motion Measuring Instruments

The ship motion-measuring instrument consists of GY521 MPU6050 3 Axis Digital Gyroscope, Accelerometer, Arduino UNO and USB Cable for Arduino UNO. Gyroscope is used for measurement of the three angles i.e. roll, pitch and yaw and accelerometer is used for measuring acceleration in all three-axis x, y and z-axis. The wave generator control system consists of following components DRV8825 Driver with Aluminum heat sink, NEMA 17 4 Wire Stepper Motor, STM32F401 256KB ROM Black Pill Development Board, Switching Power Supply SMPS 12V 5A, FT232RL FT232 USB to Serial USB to UART TTL 5V 3.3V FTDI Module, Type C Data Cable to USB Convertor and Jumper Wires. The aluminum heat sink is attached to Stepper motor driver. The complete control system is powered from a switching power supply of 12V & 5A and is connected to the stepper motor driver. Finally, this board is connected to UART. The black pill development board is connected to laptop form which code is run, and motors strokes and RPM are controlled for desired amplitude and frequency of waves. The motor speed is within the range of 50 to 250 RPM.

Results and Discussion

A gyro sensor was fixed over the small tank. It was recalibrated before the commencement of experiment. The sampling rate of gyro sensor was 100. The gyroscope operates through Arduino UNO. A computer code is used to save the data of gyro in excel file. Originally, the gyro provides data of acceleration components in three directions and rotation in three angles. We can numerically integrate to find the velocities and displacements at specific instant of time. The motor had RPM of 150 with stroke of 200 mm and the pitch of lead screw was 2mm. The mass of small tank containing water is 2kg. The force acting on small tank is the combination of sloshing force due to water inside the small tank and force with which wave hits the ship. The experimentation part revealed some interesting facts. The sloshing force in each axis is different. It is because the acceleration in these axis are different resulting in different values of forces. In addition, the pitch motion is more as compared to roll. The results of slosh force are in accordance with motion produced by wave generator yet small in magnitude. This is because, in practice, the slosh force is different at every other point on tank wall. However, here it was assumed that pressure exerted is same on at all wall locations. It was necessary also, as there was no other way to calculate total force theoretically. Whereas there must be at least six to nine, sensors at each wall face to measure the force accurately.

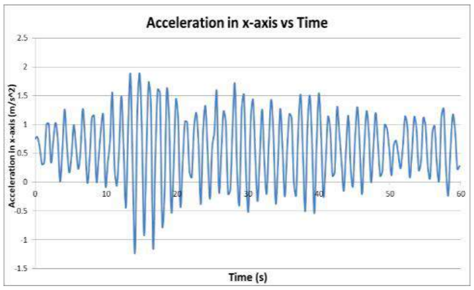

Figure 16 Acceleration in x axis

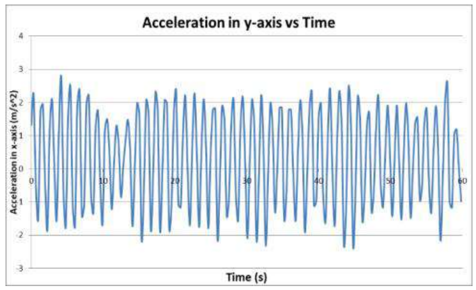

Figure 17 Acceleration in y axis

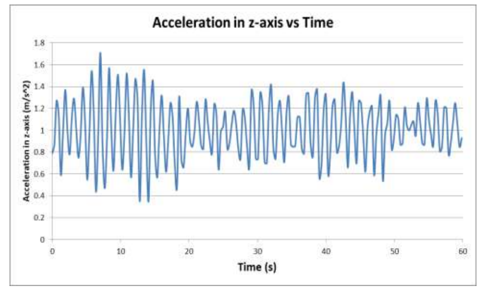

Figure 18 Acceleration in z axis

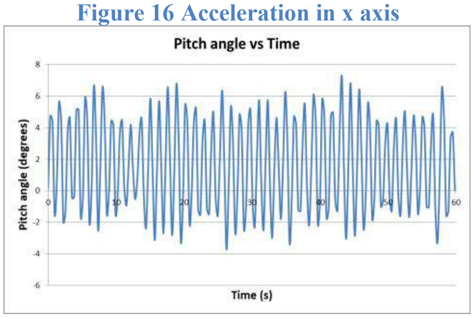

Figure 19 Pitch angle in degrees

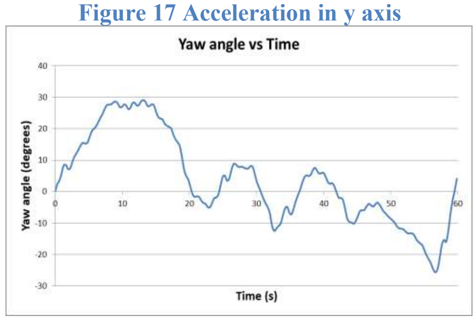

Figure 20 Yaw angle in degrees

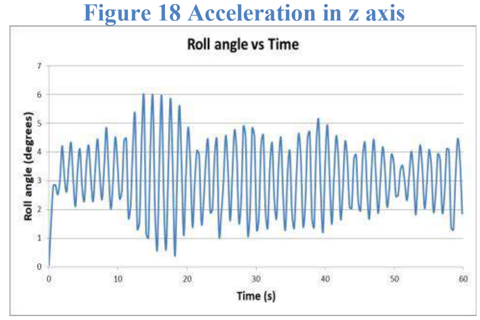

Figure 21 Roll angle in degrees

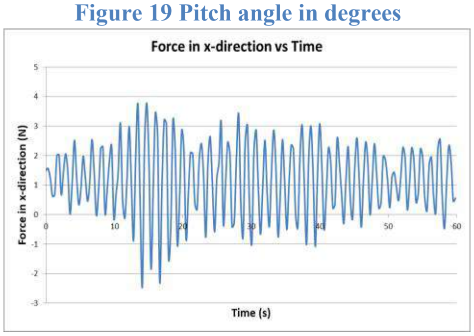

Figure 22 Force in x direction

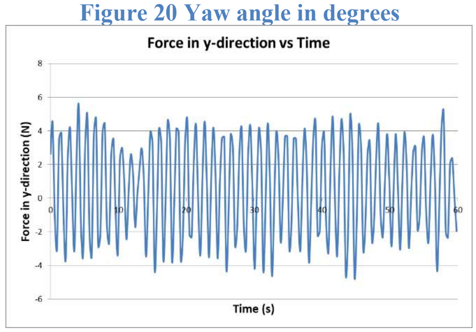

Figure 23 Force in y direction

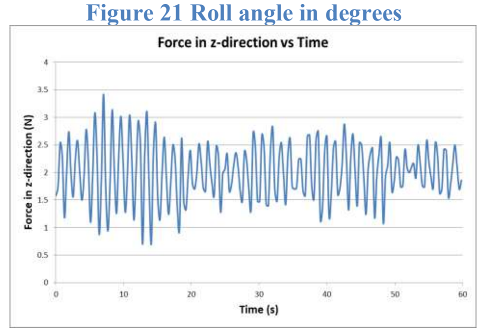

Figure 24 Force in z direction

Conclusion

The focus of this study is on design and development of sloshing set up. Commercially available apparatus to study sloshing in six degrees of freedom is hexapod which is an expensive equipment. The main goal of this study is to develop indigenous equipment that could capture sloshing with reasonable accuracy. Experiments were performed to study designated parameters and motion of ship with degree of freedom. The designated parameters are visualization of sloshing motion inside the tank using ship-based excitation.

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