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Design and Development of a Cheap Slosh Testing Rig as Laboratory Equipment

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Abstract

Liquid sloshing in container is a classic problem in fluid mechanics and many other engineering fields. Due to the complexity of fluid dynamics, sloshing is studied using analogical model. Different equivalent mechanical model of sloshing phenomena have been developed in the last century [4,6,7,9]. Each of these models can predict the sloshing behavior of fluid with a fairly good accuracy, but within some practical limit. As a result, sloshing is still a burning research topic in more modern fields like aerospace. The apparatus used for studying sloshing through experimentation, is called a "Slosh Testing Rig". Building a full-fledged Slosh testing rig is very expensive due to the costly 6DOF load sensors, precise data acquisition boards and actuators. Recently, a very cheap slosh testing rig has been built using local technology for the hydrodynamics lab of Department of NAME, BUET as a part of the academic thesis. The rig has 1Degree of freedom. Cheap microcontroller based data acquisition boards and several single axis load cells were used to lessen the cost. This paper contains the overall description of this rig.

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Keywords: Sloshing; Free surface effect; Slosh testing rig; Load cell; accelerometer

1. Introduction

The present trend of dealing with the sloshing phenomena is apparently the usage of computational fluid dynamics (CFD). Usage of CFD minimizes various costs regarding the experimentations. However experimental results are more preferredby the scientific community because of the limitations of CFD. Experimentations regarding sloshing needmultidimensional equipment, consisting of mechanical, electrical and software part. A good setup requires expensive mechatronic system too for creating the excitation. In recent days, many researchers have created their own test beds for studying sloshing, [1–5]. Specially, the one in IIT Bombay is very impressing, [1,6,8]. This rig is very expensive as it uses a 6DOF load cell along with powerful data acquisition and mechatronic system.

In our research project, we focused to build a simple, easy to use, low cost apparatus for conducting experiments regarding sloshing phenomena. This was done by a novel approach. A combination of accelerometer and single axis load cell provided the way to determining the sloshing phenomena in a rectangular box. As the accelerometer is capable of measuring external force of any magnitude, there is no need for controlled excitation. Thus the necessity of any mechatronic system mitigates, which makes the testing rig as simple as only a combination a single axis load cell and a triple axis accelerometer.

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2. Concept

As the liquid in a container sloshes, the center of gravity of the liquid shifts along the axis of the exerted force. If we know the volume, i.e. the total mass of the liquid and the exact geometry of the container, a single axis load cell installed at one end of the container is enough to find out the overall displacement of the liquid in the tank. In order to study the relationship between the displacement and the force, an accelerometer is attached on one side of the container. As the effective influence of the force on the container is the acceleration it creates, measuring the acceleration is enough.

3. Design

The main part of the testing rig is a rectangular container, which has a length of 19cm. The breadth and height of the container is 9 cm and 15 cm respectively. The container is attached on an aluminum frame which is also rectangular in shape. One side of the container is directly bolted on the frame and the other side is bolted through a 5 KG load cell. As we pour water into the container, the load cell indicates the increment of force, i.e. weight on it. When the container is oscillated, that means the C.G. of the water changes, the distance of the C.G. from the load cell changes too. As a result, the component of weight acting on the load cell changes. This is detected by reading the output of the load cell. The output of the load cell is very tiny analog voltage. To make it sensible to the microcontroller, a voltage amplifier was needed. For this purpose, we have used HX711 24 bit analog to digital converter IC. It is used extensively with load cells.

To measure the acceleration caused by the force, a triple axis accelerometer was installed. The accelerometer gives analog output in a range which is directly readable using microcontroller. The main CPU was built using an Arduino UNO, which is a popular open source hardware prototyping board based on ATMEL's ATmega 328 microcontroller.

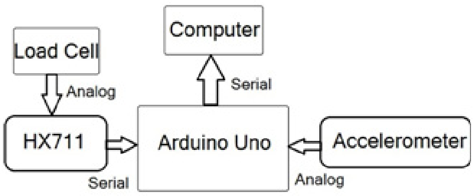

Fig. 1: Block diagram of the system

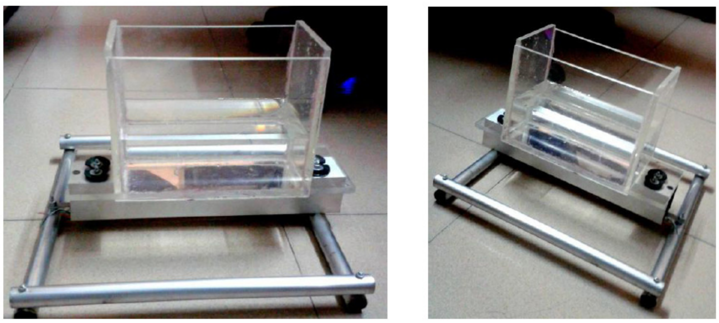

Fig. 2: Slosh Testing Rig: The structure

4. Calculations and mathematical model

The force or component of weight on the load cell at a certain moment can be derived from the output value of the HX711 chip using the following expression:

$$W_s = m \times ADC + C$$

Where, the value of m and C are constant and must be determined in the calibration process. This component of weight, W_s depends on the total weight of the liquid and the longitudinal position of its center of gravity. If X is the distance between two supports, then we can write the following equations where subscript r and s represents the rigid support and sensor respectively.

$$W_s = W \times \frac{X_r}{X}$$
$$X_r = X \times W_s W$$

Now, the total weight of the water can either be determined by pouring definite amount of liquid into the tank or mathematically from load cell reading at equilibrium state. When, there is no oscillation, the longitudinal C.G. of the liquid is at the longitudinal C.G. of the tank, which can be measured geometrically. Let the distance of that C.G. from the rigid support of the sensor is $x_C G$. Then,

$$W = W_s \times \frac{X}{X_{CG}}$$

So, we can summarize the mathematical model stating these workable formula:

$$W = \frac{X}{X_{CG}} \times (m \times ADC + C)$$
$$\Rightarrow W = m'_{CG} \times ADC + C'_{CG}$$

$$Where,\ m'_{CG} = m \times \frac{X}{X_{CG}}$$
$$and\ C'_{CG} = C \times \frac{X}{X_{CG}}$$

Similarly,

$$X_{CG} = \frac{1}{W} \times (m'ADC + C')$$

$$Where,\ m' = m \times X$$
$$and\ C' = C \times X$$

5. Calibration

Before using, the load cell and the accelerometer needed to be calibrated first. The calibration process was done after building up the rig completely in order to compensate any change in characteristics during the building period.

5.1. Load cell Calibration

The tank was first emptied. Then weighed water was poured into the tank successively for a couple of times. Each time, the reading of the 24-bit ADC chip was taken. After finishing, the data was taken into MATLAB to fit a curve on the dataset. As expected, the curve was found to be linear.
After curve fitting, we get the optimum values as-

$$m'_{CG} = -3508.327 \times 10^{-8}, \quad C'_{CG} = -6301.514 \times 10^{-6}$$

Where value of X and X_{CG} were measured by hand and found to be-

$$X = 28cm, X_{CG} = 12.5cm$$

Table 1: Data for load cell calibration

No.	Water present (KG)	Weight of water + Container (KG)	Weight of the container after pouring (KG)	Mass of water (KG)	ADC value
1	0	0.68	0.05	0.63	-18298
2	0.63	0.49	0.04	1.08	-30855
3	1.08	0.51	0.05	1.54	-43871
4	1.54	0.35	0.05	1.84	-52582
5	1.84	0.29	0.05	2.08	-59663

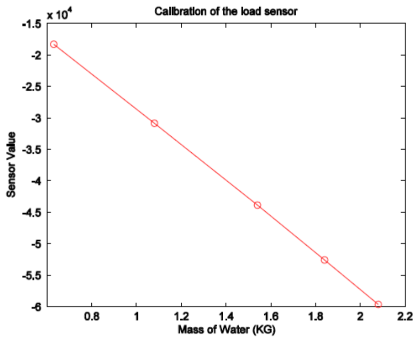

Fig. 3: Calibration of the load cell. The decrement of the ADC value, i.e. voltage with increment of load is due to the reverse connection of the load cell with the amplifier, which do not affect the accuracy

So,

$$m \times \frac{28}{12.5} = -3508.327^{-8}$$
$$\Rightarrow m = -1566.217 \times 10^{-8}$$

Similarly,

$$C = -2813.176 \times 10^{-6}$$

5.2. *Accelerometer Calibration*

Analog-output accelerometers give linear output voltage just like the load cell. For the calibration purpose, we needed at least two known accelerations. We have used the gravitational acceleration of earth for this step. X-axis of the accelerometer was placed straight downward, upward and horizontal with respect to the ground to have exerted acceleration of 9.81 m/s^2, -9.81 $m/s^2$and 0 m/s^2respectively.

Table 2: Calibration of the accelerometer

Exerted acceleration (m/s^2)	ADC value		
	Experiment 1	Experiment 2	Average
9.81	301	273	287
0	347	351	349
-9.81	409	408	408.5

From the above data set, we get the following relationship:

$$Acceleration = -0.1614587 \times ADC + 56.21454$$

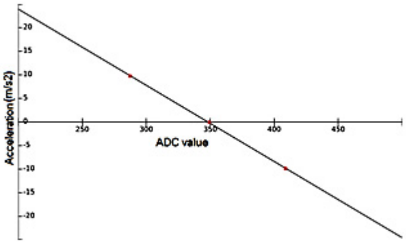

Fig. 4: Calibration of the Accelerometer. X axis represents ADC value and Y axis represents the corresponding acceleration

6. Demo experiments

In order to test the basic functionality of our rig, we have conducted some demo experiments and analyzed the data recorded. In this phase we did not check the accuracy, rather just checked the overall pattern of the component of weight on the sensor while the water inside the tank oscillates due to single external impact. The damping effect of sloshing should decrease exponentially [7,9], which is also seen in the graphs of the experimental data given below.

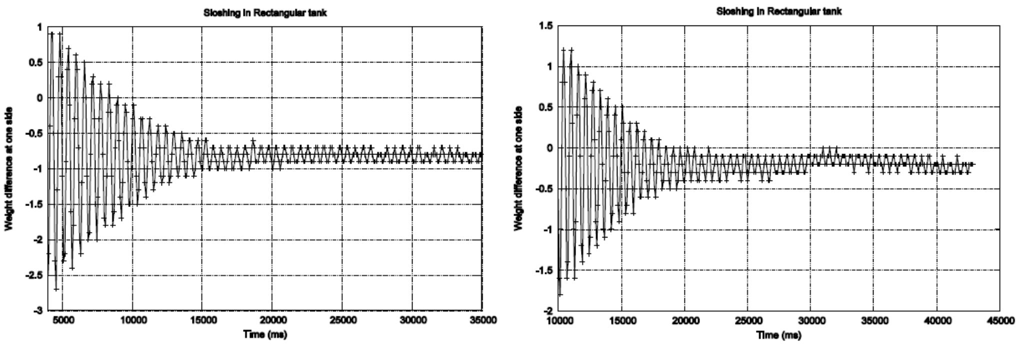

Fig. 5: Graphs showing weight (in Newton) on the sensor at different time at demo experiment 1 and 2. Sinusoidal change of weight on sensor along with the exponential decrement of the oscillating fluid is clearly visible in both graphs

7. Cost assessment

The prime concern of this project was to minimize the cost as much as possible. Cost of different parts of the rig are given in the table below:

Table 3: Cost assessment of the slosh rig

Item	Quantity	Cost (In BDT)
5kg Load cell	1	800
HX-711 module		400
ADXL 335 analog Accelerometer	1	350
Arduino Uno	1	600
8 mm acrylic sheet for tank	2x1 square feet	500
Thai aluminum rod for supporting structure	4 feet	200
Total		2850 BDT = 37 USD

8. Conclusion

The total cost for building the test bed is very reasonable. This was our prime target. Besides, from the data obtained from the demo experiments, the rig seems to have a promising potential. However, the actual accuracy and thus thereliability is still in question as they are not yet assessed mathematically. In fact,this experimental setup was built for another theoretical research on sloshing problem, which is yet to be completed. Investigations regarding the actual accuracy and reliability will be carried out after the completion of that research. Present lack of data regarding the accuracy is in fact a drawback of this system. But this will be mitigated within no time prior to its usage.

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