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Development of 2DOF Actuation Slosh Rig: A Novel Mechatronic System

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Abstract— **Sloshing of liquid in a tank is important in several areas including launch vehicles carrying liquid fuel in space application, ships, and liquid cargo carriages. Hence modeling and characterization of nonlinear slosh dynamics is critical for study of dynamics of these systems. Additionally control of sloshing liquid offers a challenging problem of control of underactuated systems. To study slosh dynamics, develop useful identification schemes, and design and verify slosh control algorithms, a new 2DOF actuation slosh rig is reported in this paper considering the fact that most of the times the liquid tanks are subjected to linear as well as pitching excitation. The paper discusses mechatronic design and several advantages offered by the new design. Furthermore, a mathematical model of the rig is developed using Lagrange formulation assuming two-pendulum model for slosh. Slosh parameter identification with the rig is demonstrated in pitching and linear excitation cases. Nonlinear parameter identification schemes developed using simplified version of rig model are used for the purpose. Further results on compensation of slosh and rotary slosh phenomena are presented. Thus the proposed rig is ideal tool for study, identification, and control of slosh phenomena.**

I. Introduction

Detrimental effects of liquid sloshing are experienced in a number of areas, including the transportation of liquid cargo, storage of liquid in tanks, aircraft, and launch vehicle fuel tanks. In launch vehicles or spacecraft, for example, tank motions resulting from guidance and control system commands or from changes in vehicle acceleration and can induce sloshing. As the fuel is consumed and liquid level changes with time, slosh dynamics can be further complicated and make the system unstable. A slosh-induced instability may lead to structural failure, drift from desired trajectories, higher fuel consumption, premature engine shutdown or inability of the spacecraft to achieve upper-stage engine start. A recent article by Vreeburg [1] presents some examples of failures caused by sloshing.

It is important to study and characterize the phenomenon of sloshing, to develop, identify, and experimentally verify simple mathematical models of slosh that can be used for mission simulation and control development. For reliable mission simulation, these models must capture the true dynamic behavior of the liquid as will be seen by the vehicle carrying the tank.

Literature on slosh characterization [2], [3], [4], [5], [6], [7], [8], shows that either linear or pitching or spinning excitation has been provided to the tank to capture the motion dynamics of interest. Widmayer et al. [2] used pitching excitation for a tank held by means of a torsion bar. Several researchers [3], [4], [6], [5] have reported experimental study of slosh using linear excitation and results are compared with that obtained from analytical and FEM models. More recently Gangadharan et al. [8] have reported Spinning Slosh Test Rig (SSTR).

Thus to the best of our knowledge, a two simultaneous DOF excitations have not been reported thus far. However, the actual motion of vehicle carrying the tank (may be rocket or satellite or aircraft) may involve both linear part and rotational part simultaneously also not necessarily in the same plane. So the motion of liquid with both these excitations being a nonlinear phenomenon can be quite complex than that with a single DOF excitation. Thus, for more realistic study, it is important to provide motion to the tank, which is closer to the actual motion experienced by the tank in launch vehicles. Even otherwise, study of nonlinear slosh dynamics, identification and control with two DOF actuation would be quite interesting and challenging academically. With this motivation, this paper proposes a new test rig with 2- DOF actuation.

Another important point with the proposed design is improvement in the measurement scheme. The proposed design uses a novel idea of mounting a six axis force transducer right at the base of liquid tank. This, as we will see later, avoids need for expensive pressurized oil film suspension to reduce friction noise in the measurement of forces and moments. This design will bring down drastically the cost of scaled versions for actual space vehicle tanks. Several experiments carried out with the rig verifies its effectiveness at accurate measurement of slosh forces and moments in all the directions.

From academic perspective, the rig offers a platform to study, characterize, and further develop control algorithms for complex fluid motions with simultaneous excitations of both the DOFs. Such studies are currently underway. Slosh control problem approximated to the first mode of slosh vibration is similar to inverted pendulum. However as higher modes get excited it becomes more complex and challenging to develop nonlinear control strategies.

This paper is organized as follows. Section II presents mechatronics system of the proposed rig. Sensors, actuators, controller and plant are discussed in this section. Several advantages offered by this new mechatronics de-

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sign are presented. Section III presents Lagrange formulation of nonlinear system dynamics of the rig. Results of experiments carried out to successfully identify slosh parameters with linear and pitching excitation are presented in Section IV. Some interesting experimental results of rotary slosh effects and both excitation effects are presented. Finally, Section V concludes research findings.

II. Proposed Mechatronic Design

The proposed mechatronic system has a plant consisting of mechanisms to drive tank in linear as well as pitching direction. The linear stage motion is realized using a ball screw mechanism. It carries the entire system for pitching motion. Ball screw arrangement also provides speed reduction and increase in the linear force necessary to drive the liquid tank. This arrangement is less expensive than electrodynamic shaker [5], [6] or hydraulic actuator [4] used previously for linear DOF excitation but gives the same positioning accuracy for excitation waveform. Another ball screw arrangement is used to drive the pitching stage through slider crank mechanism where the driver is slider realized using ball screw mechanism. The schematic of the mechanisms is shown in Figure 1.

The CG of the tank is matched with the hinge location for the pitching joint. This arrangement helps to get pure pitching motion of liquid. With different fill fractions of liquid in the tank the CG will move off the hinge location by small amount. This can be compensated by adjusting height of the tank on the base. The setup can be converted into 1-DOF actuation by holding linear or pitching actuation. Mechanical locking arrangements are provided for both the degrees of freedom for this purpose.

Moreover, arrangement is provided to rotate the axis of the pitching DOF (with respect to direction of linear motion) in the horizontal plane by 150 degrees. Using this arrangement various possible cases of excitation can be studied. For example, linear motion in one direction and pitching motion of the tank giving excitation in the perpendicular direction can be possible. The six axis load cell would measure the slosh forces and moments coming on the tank with this excitation. The photograph of the rig depicted in Figure 2 shows the assembly of mechanisms for linear and pitching motion along with the respective motors.

Sensors: Another novel part in the design of the proposed rig is use of six-axis force transducer. To measure forces, the previous designs [3], [4], [6], [5] used a single axis force transducer or two force sensors for moment measurement. With this instrumentation, forces and moments generated due to sloshing in all other directions could not be measured. Thus, for example, the effect of linear excitation in other directions could not be measured. Hence it is proposed to incorporate a six-axis load cell directly below the tank in our new design. This will capture forces and moments due to sloshing in all directions and several cases of slosh excitation (including rotary slosh) can be characterized.

This location of six axis load cell gives another advantage. Previous rigs used pressurized oil film to support the tank to minimize the friction which corrupt their slosh data with frictional force. The location of load cell below the tank in the proposed design naturally overcomes this problem. Figure 3 shows schematically the previous and the proposed way to clarify the point. Thus in the proposed design, efforts and expenses of putting pressurized oil film or any such other means to reduce friction can be avoided and at the same time accuracy of measurement of forces and moments is improved.

Other sensors in the system include encoders used to measure both the motor positions. These are mounted integral with the brushless DC servomotors. The encoder

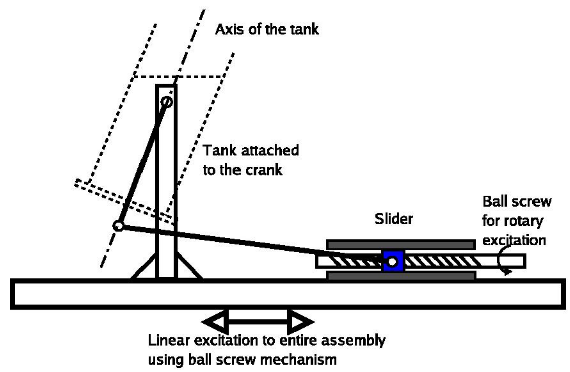

Fig. 1. Mechanism of pitching excitation

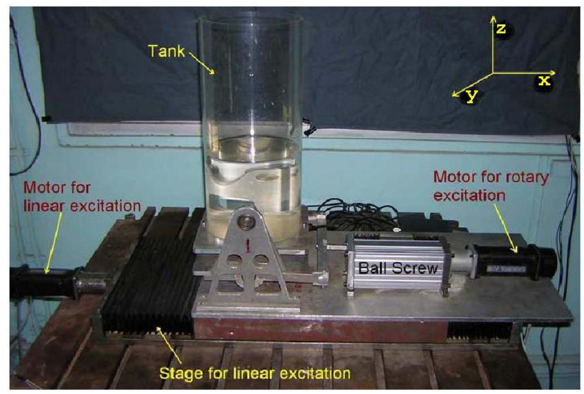

Fig. 2. Photograph of slosh rig interfaced with PC

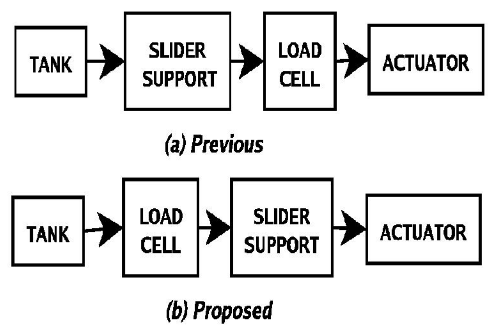

Fig. 3. Schematic diagram illustrating placement of load cell

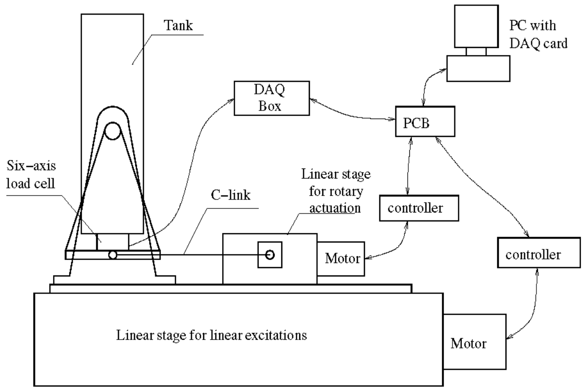

Fig. 4. Schematic diagram of slosh rig interfaced with PC

output is quadrature; hence position resolution of 1.25 μm is obtained considering reduction in the ballscrew assembly. Thus relatively low resolution positioning sensors (encoders) can be used without sacrificing resolution of tank linear and pitching motion.

Actuators: The design of actuators (in terms of the power) is carried out to drive the rig at least with first three modal frequencies of sloshing. The actuation is carried out using brushless DC servomotors from Jayashree Electrodevices Pvt Ltd. The motion control drives are configured to run these motors in torque control mode based on analog input. The required analog control signal is provided by using analog channels of dSPACE [9] 1104 card.

Interface: Sensor signals are captured and actuators are controlled using SIMULINK and dSPACE DAQ card interface. Six ADCs capture signals from six axes of the load cell (3 moments about x,y,z axes and 3 forces in x,y,z direction). These sensor signals are filtered using second order filter to remove unwanted noise. Two quadrature encoder interfaces capture motor position data. Based on feedback from encoders, a control torque signal is generated for each motor. The torque control signal is implemented on motors through two DACs of the dSPACE. Figure 4 shows the schematic of the rig interfaced with PC.

Control: For the proposed rig any linear or nonlinear control strategies for either slosh analysis, identification, or control purpose can be programmed in SIMULINK and implemented using dSPACE. For preliminary experiments PID controllers were programmed for both motors using encoder position feedback to give sinusoidal and other excitation of desired amplitude and frequency to the rig. Gains were tuned to minimize the error between the actual and the desired position. Thus a variety of excitations and corresponding slosh dynamic studies can be performed based on the force and moment data.

III. Model of the Rig

This section develops mathematical model of the proposed slosh rig using Lagrange method and assuming two pendulum model of the slosh. Figure 5 shows the schematic diagram defining all the variables and parameters used. Total mass of liquid is divided into rigid mass and the slosh mass in the first and second pendulum. The kinetic energy (KE) and potential energy (PE) of system as sum of those of individual elements are obtained as

$$\begin{aligned}
KE &= \tfrac{1}{2}m_l\dot{x}^2 + \tfrac{1}{2}m_p\dot{x}^2 + \tfrac{1}{2}(I_p + m_pk^2)\dot{\theta}^2 \\
&-m_pk\dot{\theta}\dot{x}\cos\theta + \tfrac{1}{2}m_{s1}\dot{x}^2 + \tfrac{1}{2}(I_{s1} + m_{s1}l_{pe1}^2)(\dot{\theta} + \dot{\phi}_1)^2 \\
&+\tfrac{1}{2}m_{s1}r_1^2\dot{\theta}^2 + m_{s1}\dot{x}l_{pe1}\cos(\theta + \phi_1)(\dot{\theta} + \dot{\phi}_1) \\
&-m_{s1}r_1\dot{x}\dot{\theta}\cos\theta - m_{s1}r_1l_{pe1}\cos\phi_1(\dot{\theta}^2 + \dot{\theta}\dot{\phi}_1) \\
&\tfrac{1}{2}m_{s2}\dot{x}^2 + \tfrac{1}{2}(I_{s2} + m_{s2}l_{pe2}^2)(\dot{\theta} + \dot{\phi}_2)^2 \\
&+\tfrac{1}{2}m_{s2}r_2^2\dot{\theta}^2 + m_{s2}\dot{x}l_{pe2}\cos(\theta + \phi_2)(\dot{\theta} + \dot{\phi}_2) \\
&-m_{s2}r_2\dot{x}\dot{\theta}\cos\theta - m_{s2}r_2l_{pe2}\cos\phi_2(\dot{\theta}^2 + \dot{\theta}\dot{\phi}_2), \qquad (1)
\end{aligned}$$

$$\begin{aligned}
PE &= -m_pgk\cos\theta + m_{s1}gh_1 + m_{s1}gr_1\cos\theta \\
&-m_{s1}gl_{pe1}\cos(\theta + \phi_1) + m_pgh_1 + m_{s2}gh_1 \\
&+m_{s2}gr_2\cos\theta - m_{s2}gl_{pe2}\cos(\theta + \phi_2). \qquad (2)
\end{aligned}$$

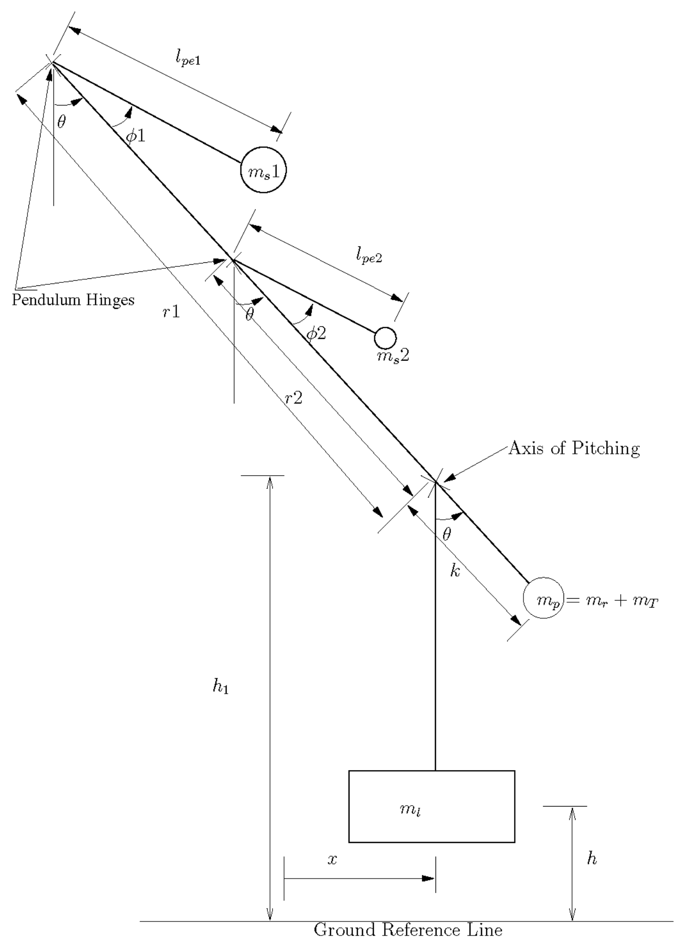

Fig. 5. Model of rig under co-planar pitching and translation excitation considering two pendulum slosh

Using these expressions we form Lagrangian as $L = KE - PE$. Using standard Lagrange equation with x, θ, and ϕ_i as generalized coordinates we obtain the equations of motion of the entire system as follows:

$$F_x - C_x\dot{x} \quad = \quad \frac{\partial}{\partial t}\frac{\partial L}{\partial \dot{x}} - \frac{\partial L}{\partial x},$$

$$
\begin{aligned}
T_\theta - C_\theta \dot{\theta} &= \frac{\partial}{\partial t}\frac{\partial L}{\partial \dot{\theta}} - \frac{\partial L}{\partial \theta}, \\
-C_{\phi_1}\dot{\phi}_1 &= \frac{\partial}{\partial t}\frac{\partial L}{\partial \dot{\phi}_1} - \frac{\partial L}{\partial \phi_1}, \\
-C_{\phi_2}\dot{\phi}_2 &= \frac{\partial}{\partial t}\frac{\partial L}{\partial \dot{\phi}_2} - \frac{\partial L}{\partial \phi_2}.
\end{aligned} \tag{3}
$$

Working out the partial derivatives and simplifying further we obtain the following four second order differential equations of system dynamics:

$$
\begin{gathered}
F_x - C_x\dot{x} = (m_l + m_p + m_{s1} + m_{s2})\ddot{x} + [m_p k\cos\theta \\
+ m_{s1}l_{pe1}\cos(\theta+\phi_1) + m_{s2}l_{pe2}\cos(\theta+\phi_2) \\
- m_{s1}r_1\cos\theta - m_{s2}r_2\cos\theta]\ddot{\theta} + m_{s1}l_{pe1}\cos(\theta+\phi_1)\ddot{\phi}_1 \\
+ m_{s2}l_{pe2}\cos(\theta+\phi_2)\ddot{\phi}_2 + [-m_p k\sin\theta + m_{s1}r_1\sin\theta \\
- m_{s1}l_{pe1}\sin(\theta+\phi_1) + m_{s2}r_2\sin\theta \\
- m_{s2}l_{pe2}\sin(\theta+\phi_2)]\dot{\theta}^2 + [-m_{s1}l_{pe1}\sin(\theta+\phi_1)]\dot{\phi}_1^2 \\
+ [-m_{s2}l_{pe2}\sin(\theta+\phi_2)]\dot{\phi}_2^2 + [-2m_{s1}l_{pe1}\sin(\theta+\phi_1)]\dot{\theta}\dot{\phi}_1 \\
+ [-2m_{s2}l_{pe2}\sin(\theta+\phi_2)]\dot{\theta}\dot{\phi}_2,
\end{gathered} \tag{4}
$$

$$
\begin{gathered}
T_\theta - C_\theta\dot{\theta} = [m_p k\cos\theta + m_{s1}l_{pe1}\cos(\theta+\phi_1) \\
- m_{s1}r_1\cos\theta + m_{s2}l_{pe2}\cos(\theta+\phi_2) - m_{s2}r_2\cos\theta]\ddot{x} \\
+ [I_p + m_p k^2 + I_{s1} + m_{s1}l_{pe1}^2 - 2m_{s1}r_1 l_{pe1}\cos\phi_1 \\
+ m_{s1}r_1^2 + I_{s2} + m_{s2}l_{pe2}^2 + m_{s2}r_2^2 - 2m_{s2}r_2 l_{pe2}\cos\phi_2]\ddot{\theta} \\
+ [I_{s1} + m_{s1}l_{pe1}^2 - m_{s1}r_1 l_{pe1}\cos\phi_1]\ddot{\phi}_1 \\
+ [I_{s2} + m_{s2}l_{pe2}^2 - m_{s2}r_2 l_{pe2}\cos\phi_2]\ddot{\phi}_2 \\
+ [m_{s1}r_1 l_{pe1}\sin\phi_1]\dot{\phi}_1^2 + [m_{s2}r_2 l_{pe2}\sin\phi_2]\dot{\phi}_2^2 \\
+ [2m_{s1}r_1 l_{pe1}\sin\phi_1]\dot{\theta}\dot{\phi}_1 + [2m_{s2}r_2 l_{pe2}\sin\phi_2]\dot{\theta}\dot{\phi}_2 \\
+ [m_p g k\sin\theta - m_{s1}g r_1\sin\theta + m_{s1}g l_{pe1}\sin(\theta+\phi_1) \\
- m_{s2}g r_2\sin\theta + m_{s2}g l_{pe2}\sin(\theta+\phi_2)],
\end{gathered} \tag{5}
$$

$$
\begin{gathered}
-C_{\phi_1}\dot{\phi}_1 = [m_{s1}l_{pe1}\cos(\theta+\phi_1)]\ddot{x} + [I_{s1} + m_{s1}l_{pe1}^2 \\
- m_{s1}r_1 l_{pe1}\cos\phi_1]\ddot{\theta} + [I_{s1} + m_{s1}l_{pe1}^2]\ddot{\phi}_1 \\
+ [-m_{s1}r_1 l_{pe1}\sin\phi_1]\dot{\theta}^2 + m_{s1}g l_{pe1}\sin(\theta+\phi_1),
\end{gathered} \tag{6}
$$

$$
\begin{gathered}
-C_{\phi_2}\dot{\phi}_2 = [m_{s2}l_{pe2}\cos(\theta+\phi_2)]\ddot{x} + [I_{s2} + m_{s2}l_{pe2}^2 \\
- m_{s2}r_2 l_{pe2}\cos\phi_2]\ddot{\theta} + [I_{s2} + m_{s2}l_{pe2}^2]\ddot{\phi}_2 \\
+ [-m_{s2}r_2 l_{pe2}\sin\phi_2]\dot{\theta}^2 + m_{s2}g l_{pe2}\sin(\theta+\phi_2).
\end{gathered} \tag{7}
$$

F_x is the force on the liner motion x stage, T_θ is torque in the direction of pitching excitation, C_x, and C_θ are damping in x and θ direction respectively. These equations which are fairly general can be used to simulate the motion of rig and sloshing liquid for various cases. We use them in the next section for identification of slosh pendulum model parameters and slosh compensation.

IV. Results

This section presents simulation and experimental results of various cases that demonstrate the effectiveness of

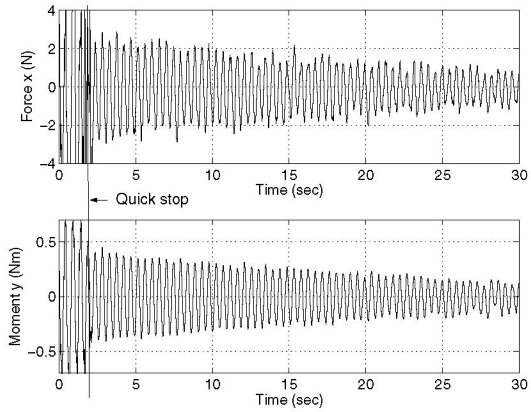

Fig. 6. Forces and moments on the tank for 5kg liquid mass

the proposed rig. First set of experiments are carried out to identify various slosh parameters for pendulum model using classical linear DOF excitation [7,3] for cylindrical tank with several fill fractions. Sinusoidal excitation close to the first mode of vibration and then a quick stop is used to allow liquid to follow its natural first mode of vibration. From recorded force (Fx) and moment (My) data (see Figure 6) various parameters including natural frequency, slosh mass, damping, and pendulum hinge location are identified and compared with the analytical and experimental data in [3]. A simplified version (considering only linear DOF) of model presented in the previous section and recently developed identification schemes [10] are used for estimating various parameters. Figure 7 shows the comparison of identified slosh parameters with analytical results of [3]. We observe that the values match well within 6 % for frequencies and within 12 % for hinge location and better than similar results in [3]. This confirms the successful implementation and working of the proposed rig.

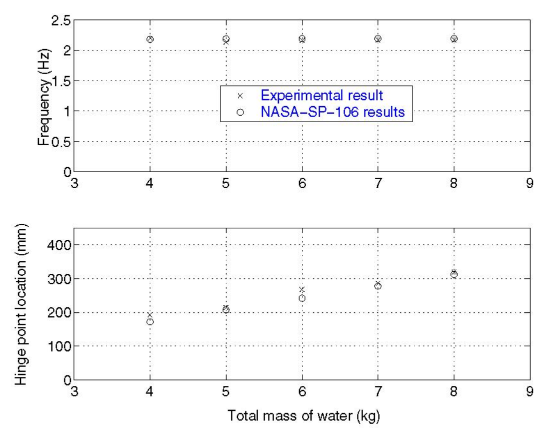

Fig. 7. Experimental and analytical values of frequencies and hinge locations

Similarly by giving excitation in pitching degree of freedom and using recently developed identification schemes, we obtained liquid moment of inertia. A simplified version (considering only pitching DOF) of the model presented in the previous section is used for this purpose. Figure 8 shows comparison of the values identified from experimental data and those from [3]. The experimental estimates are higher than theoretical values. The discrepancy can be attributed to surface wiping effects and viscosity of water.

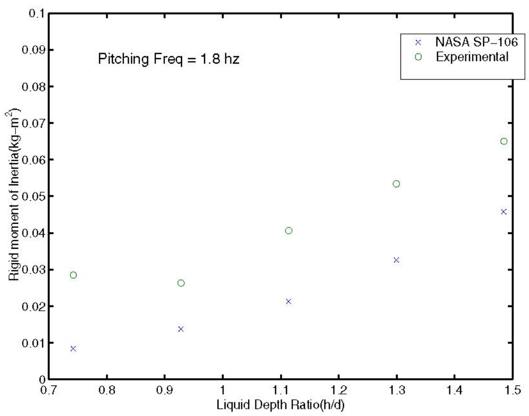

Fig. 8. Experimental and analytical values of liquid inertia estimates

Investigation has also been carried out in excitation in pitching and implementing control compensation in linear DOF such that there is no slosh. Model developed in the previous section is used to determine the amplitude and phase of excitation. Figure 9 and Figure 10 show simulation and experimental results respectively. We observe that the compensation implemented in linear DOF cancels slosh induced due to pitching excitation.

Additional experiments were carried out to observe rotary slosh by giving sinusoidal excitation just beyond the natural frequency. Figure 11 shows the experimental moments in two perpendicular directions on the tank. We clearly see (in the steady state after quick stop) the expected variation out of phase with each other in x and y moments. This data can be used to determine the parameters of the rotary slosh model. Several such slosh phenomena can be studied and characterized using both linear and rotary excitation facility in the proposed rig.

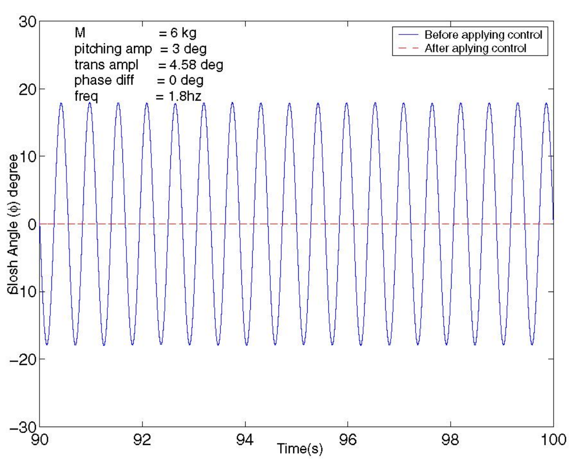

Fig. 9. Excitation in pitching and compensation in linear DOF: simulation

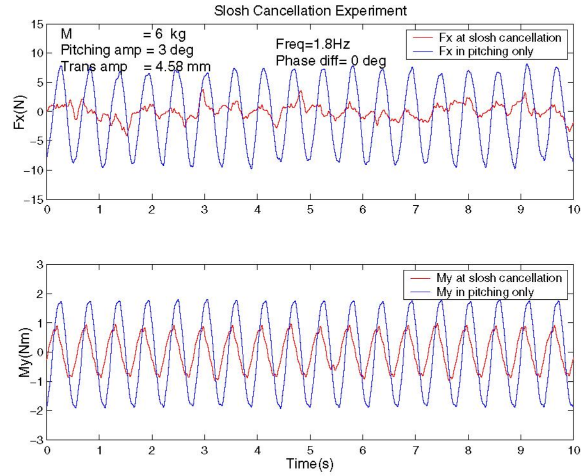

Fig. 10. Excitation in pitching and compensation in linear DOF: experiment

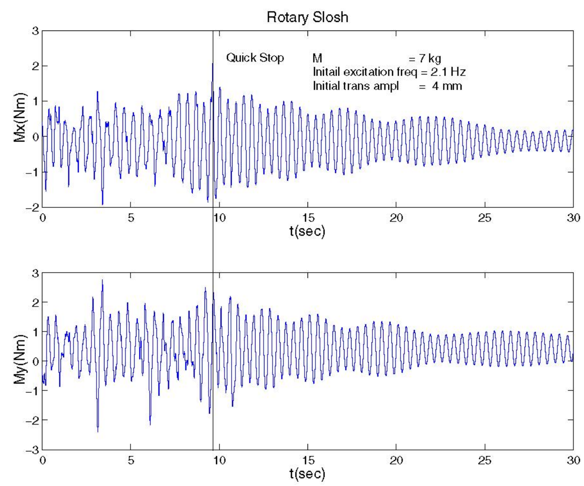

Fig. 11. Rotary slosh captured in two moments M_x and M_y

V. Conclusion

Deeper exploration of complex phenomenon, like sloshing, can be pursued more effectively with support of appropriate experimental results and techniques. The proposed 2 DOF design is capable of providing several cases of excitation of slosh by using either of them or both of them with controlled phase lag, or with axis of pitching excitation tilted with respect to the direction of linear motion and so on. For the first time a six-axis load cell is used to measure slosh forces and moments in all direction; hence the proposed rig facilitates study of wide variety of slosh phenomena. Experimental results of identification of slosh parameters in traditional way match well with theoretical results confirming the successful operation of the proposed rig. Sample set of experimental results are presented to further demonstrate some of the capabilities of the rig.

The new proposed rig opens up several avenues of analysis, identification, and control of slosh both from academic as well as industrial application perspective. For example the actual mission trajectory data can be fed to the rig and estimation of slosh force and moments in actual launch vehicle can be done, new nonlinear slosh control strategies could be developed and verified experimentally, and slosh with various damping structures (baffles) can be characterized for forces and moments in all directions. Thus the proposed rig has immense potential for both teaching and research in the identification, modeling, and control of slosh.

ACKNOWLEDGMENT

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