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ABSTRACT

The phenomenon of sloshing is a substantial challenge in propellant management, particularly in reduced gravity where surface tension-driven flows result in large slosh amplitudes and relatively long decay time scales. Propellant Management Devices (PMDs) such as the rigid baffles and elastomeric membranes are often employed to counteract motion of the free surface. In the present study, we investigate an active PMD that utilizes a free-floating membrane that, under an applied static magnetic field, becomes rigid and suppresses slosh. This semi-rigid structural layer can thereby replace bulky baffle structures and reduce the overall weight of the tank. In this paper, the membrane was fabricated using Metglas 2714A alloy in a weave pattern and the experiment was run for varying slosh amplitudes at a given magnetic field gradient using the slosh research facility at Embry Riddle Aeronautical University. The resultant force acting on the walls of the cylinder is recorded for each test run using a pair of load cells that are attached at the end of each movable arm. Computational Fluid Dynamics (CFD) simulations were setup with the parameters of the experiment to verify and validate the experimental setup. The result of this investigation provides information on the magnetic field gradient required to control certain amplitude of slosh or in other words, the maximum amplitude of slosh that can be controlled for a given magnetic field.

Nomenclature

MAPMD	–	Magneto-Active Propellant Management Device
DAQ	–	Data Acquisition
f	–	Frequency
DFBI	–	Dynamic Fluid Body Interaction
ERAU	–	Embry-Riddle Aeronautical University

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I. Introduction

Sloshing is the movement of a liquid in a container resulting from the application of an external force while the free surface is allowed to move without any constraints. Study of liquid slosh inside a partially filled container has been investigated for many decades[1,2] . Motion of a contained liquid's free surface leads to the buildup of kinetic energy and momentum over time, which is then transferred to the walls of the container. This periodic transfer of energy in spacecraft represent a serious vehicle safety concern. Many vehicle failures and loss-of-mission[3] have been attributed to uncontrolled propellant slosh since 1957. For example, the mission of Jupiter Intermediate Range Ballistic Missile 1-B was forced to be terminated, after 93 seconds from launch. The failure of a Falcon-1, 2007 (example of a failure due to sloshing in recent times) vehicle on account of an uncontrolled slosh of LOX, resulted in roll-control difficulties and thereby a second-stage engine shut-off [4].

Research has been carried out for many years in minimizing the energy dissipation of the fuel slosh and to prevent the impact of the slosh momentum on the fuel tanks. Scientists have come up with novel inventions to counteract the forces and moments produced by the slosh known as propellant management devices (PMD), where PMD counteracts the forces and moments produced by the slosh[3]. PMD's can be classified into two types: Passive PMDs (such as diaphragm, baffle, etc.) and Active PMDs (such as acoustic membrane and hybrid-active membrane).

Passive PMDs (baffles), positioned on the wall of the tanks, tend to reduce the slosh and also provide structural integrity to the tank. These PMDs, in spite of the excellent damping effects provided, are considered to be disadvantageous as it adds to the overall structural mass of the tank making the tank heavier and thereby reducing the amount of propellant (volume) carried by the tank[5]. Passive slosh control is also found to be less effective for higher fill fractions, higher amplitude slosh and requires a mass budget to be implemented effectively. Active PMDs, on the other hand, under the action of an external stimuli move along the fluid surface bringing about a restrictive behavior of slosh. Structures such as elastomeric membranes, resistant to hydrocarbons present in the fuel are used in conjunction with a metallic substance in the manufacturing of active PMDs[6]. Elastomeric membranes are again subdivided into active and passive membranes. Active membranes limit the rapid motion of the fluid under the influence of an external stimuli as they float on top of the liquid surface. The membrane currently used in this study is an elastomeric membrane that behaves in an active manner, when subjected to a magnetic field. This thin membrane is powerful enough to generate the same damping effect as seen in Passive PMDs and the volume of the tank is thereby preserved by neglecting the bulky baffles (active PMDs). Active PMDs are also effective for any fill fraction and it can thus be concluded that active PMDs hold an upper hand over passive PMDs[7].

II. Methodology

The main goal of this research is to control the effect of sloshing on the liquid's free surface using a thin semi-rigid structural layer on the entire liquid surface. Theoretically, under micro-gravity conditions, this would act as a lid on top of the liquid surface controlling the liquid body movement in the tank.

The membrane currently used in this paper is Metglas 2714A, a membrane with high magnetic permeability[7]. The membrane is thereby capable of generating a high magnetic pull force when subjected to a small magnetic field. This pull force could be considered as a temporary increase in membrane mass on the liquid and can then be used to dampen the effects of surface slosh. Metglas 2714A membrane is fabricated by cutting the sheet in to thin strips of 1 cm width and arranging them in a weave pattern, as shown in the figure 2. Air pockets are glued to this mesh to make it float over the liquid surface. This membrane setup is then set to float on the free liquid surface and an electromagnet with a magnetic field intensity of 4.6 Gauss is placed at the bottom of the tank. A 24 V DC current is passed to the electromagnet and the ERAU test bed is turned on simultaneously. The resultant force acting on the walls of the cylinder as a function of time is recorded using a Data Acquisition (DAQ) device and the results are plotted.

A. Experimental Approach

The experiment setup (Figure 1) for studying the slosh damping characteristics of the proposed hybrid membrane consists of the slosh test bed at ERAU in which the tank is partially filled at 20% water level with an electromagnet placed at center of the tank's bottom. The electromagnet used in this research has been used in prior research projects like Electro-Active Micro Baffles at ERAU[8]. It is coated with a layer of sealant making it water proof and is connected to an external power supply of 24V.

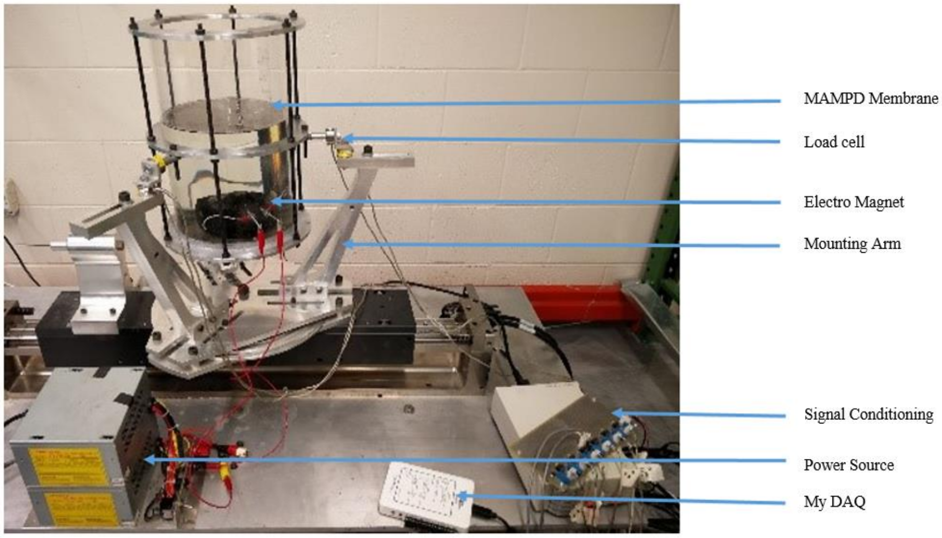

Figure 1. Experiment Setup to Study Damping Characteristics of MAPMD

The output generated by the load cells in turn attached to the tank, are recorded in the National Instruments DAQ unit coupled with a low pass filter. This filter component essentially consists of a capacitor in conjunction with a resistor and forms a passive RC low pass filter, across the positive and negative DAQ terminals. The main function of this component is to filter the noise and allow only the data signals to be read by the DAQ. The DAQ then uses the signals to calculate the force and moments acting on the tank walls. Analyzing and calculating the damping coefficient of the slosh data collected after the actuation period of 6 seconds help obtain the slosh suppression characteristics of the hybrid membrane with ease.

The experiment is conducted for two cases (Table 1). The first case is known as the free slosh characterization in which the baseline slosh values are taken and analyzed. The second case involves the usage of MAPMD wherein MAPMD is placed on top of the liquid surface. A magnetic field is then applied to which MAPMD responds as a semi-rigid structural layer thereby achieving a higher damping ratio. The slosh characterization is once again recorded.

Table1. Test Cases

	Spherical Tank and Membrane
Case 1	Free Slosh
Case 2	Slosh with non-active membrane
Case 3	Slosh with active membrane

The above mentioned cases for varying slosh amplitudes at a given magnetic field gradient are tested on the ERAU test bed and the resultant force acting on the walls of the cylinder is recorded, for each test run using a pair of load cells, attached at the end of each movable arm.

B. Computational Approach

Computational approach, employed to validate and verify the experimental results is split into two phases. The first phase involves computational finite element analysis of the sloshing liquid, without any constraints. This slosh can be considered as a free slosh. The second phase involves the finite element analysis of the behavior of the MAPMD membrane, floating over the sloshing liquid surface. The results are then compared and verified with the experimental results[9].

For the first phase, modeling of the tank is carried out in CATIA (Figure 2). The CATIA model is imported into ANSYS software. The cylindrical tank 8 inches in diameter and 12 inches in height are used in the experiment. The tank walls are assumed to be rigid and a transient analysis of the sloshing liquid is performed (as the motion of liquid varies with time). The model space inside the tank is split into an Eulerian multiphase, comprising of water and air. Free sloshing effect is then simulated by applying the standard three dimensional k-ε turbulence model. Simulation is carried out using a user-defined function that oscillates the tank at a desired frequency and time interval to obtain free slosh results.

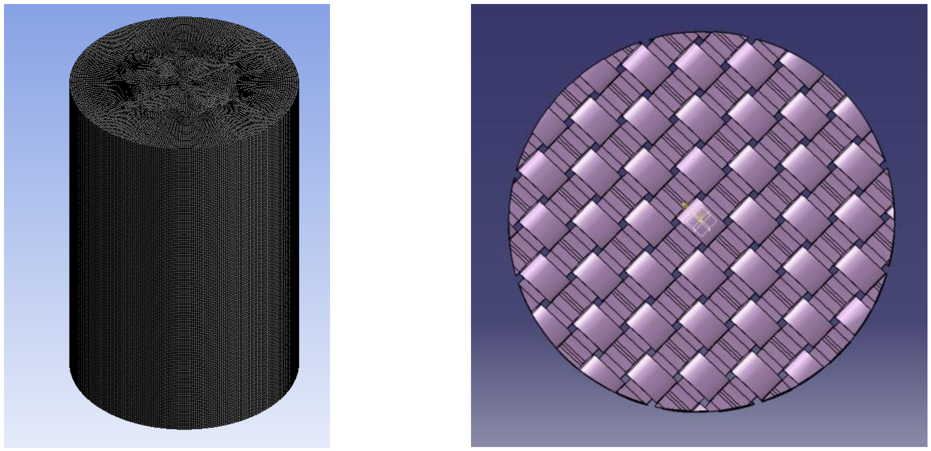

Figure 2. Model and Mesh from ANSYS

For the second phase, modeling of the membrane is carried out in CATIA and imported into ANSYS. Material properties of the Metglas 2714A alloy are provided as input to the membrane. The tank walls are then assumed to be rigid and a transient analysis of the sloshing liquid, as in the first case, is performed (as the motion of liquid varies with respect to time). The membrane is also taken as rigid body wall for initial analysis. The space inside the tank is again split into an Eulerian multiphase, comprising of water and air. Surface mesh, volume mesh & physics continua are set up for both cylindrical tank and the membrane. Overset mesh, a unique meshing condition, offered by ANSYS is used in order to replicate floating of the membrane on the surface of the liquid while the tank is under oscillating motion. This mesh moves with the motion of the body and mesh overlapping is updated at each step of the calculation. The pulling force exerted by the electromagnet is simulated by adding weights to the membrane. Dynamic Fluid Body Interaction (DFBI) is chosen in order to analyze the Fluid Structure Interaction between the membrane and water. DFBI allows for modeling of the motion of a body in response to both the forces and moments, exerted by the fluid and other external influences such as gravity. The simulation results are then verified with that of the experimental phase.

III. Results and Discussion

The simulation parameters that influence the damping force are the size of the mesh, time step chosen for the calculation and frequency of the sinusoidal excitation. Several simulations were thereby done by changing these parameters to understand their impact on the damping time and to improve the accuracy of the results. This study focuses on the X-axis forces, acting on the tank since they are the elements which disrupt the tank's stability. Several simulations with different time step and mesh size were done to choose the number of elements necessary to have a good mesh and the time step that provides satisfactory outcome with minimal computational time.

Initial simulations involving the tank without MAPMD are useful in setting up the computational domain. They are also important to assess the accuracy of the calculation as well as the relevance of the physical models chosen. The remnant slosh (slosh that occurs after the physical simulation time of 6 seconds) is studied and Figure 4 shows the comparison between preliminary experimental and computational results. It can be inferred that the damping factor is higher for CFD simulation than experiment.

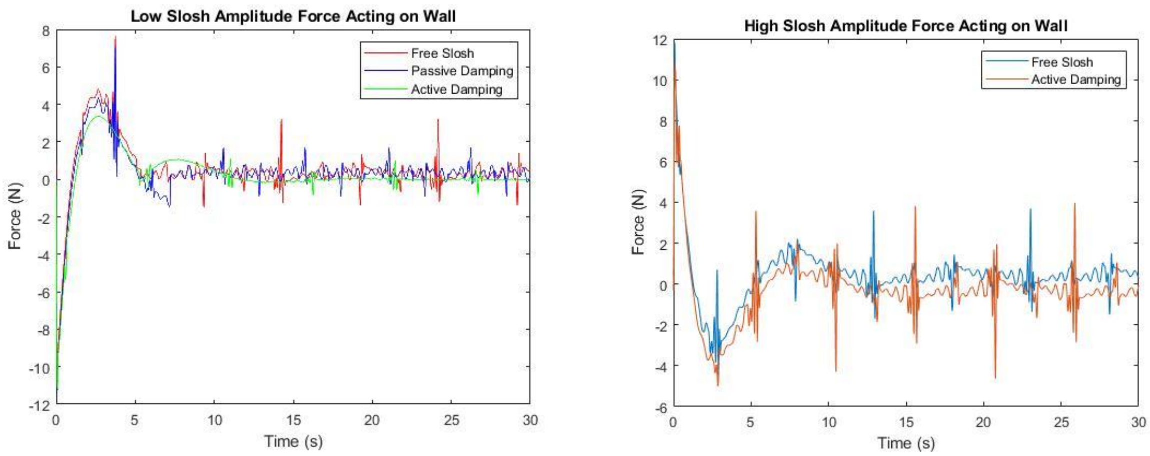

Figure 3. Comparison of Force Acting on Wall for Low and High slosh Amplitude from Experiment Results.

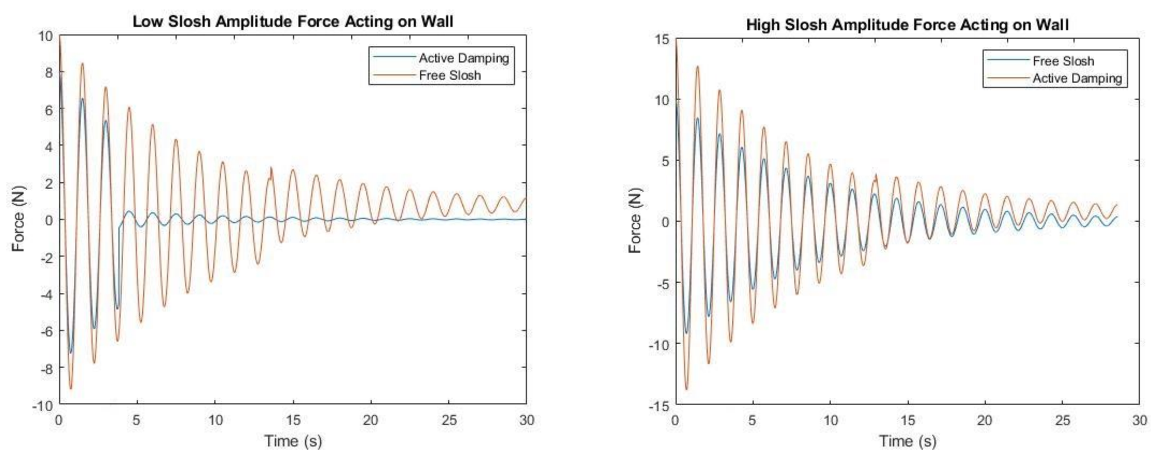

Figure 4. Comparison of Force Acting on the Wall for Low and High slosh Amplitude from CFD Results

Table 2. Damping Time for Both Free and MAPMD

Amplitude	Damping Time (s)			
	Free Slosh		MAPMD	
	Experimental	Computational	Experimental	Computational
Low slosh Amplitude (Force 2 – 8 N)	25	30	10	13
High slosh Amplitude (Force 10 – 15 N)	30	50	25	30

Experimental and computational analysis are both conducted for the same magnetic field gradient and the resultant force acting on the wall, for varying amplitudes are shown in Figures 3 and 4. The damping time for varying amplitudes are also tabulated (Table 2).

It can be concluded from the above results that the given magnetic field gradient provides effective damping for low slosh amplitudes. However, in the case of high slosh amplitudes the damping rate is found to be very low and the given magnetic field gradient if found to be ineffective in controlling the slosh.

IV. Conclusion

In this research study, initial design and development of MAPMD as a viable propellant management device along with the proof of concept experiments is carried out. Concept of hybrid membrane, acting as semi rigid structural layer under the influence of external magnetic field, floating on top of the liquid surface is laid out. In our research, Metglas 2714-A is used to fabricate the membrane and the electromagnetic force acting on the membrane is 7.1 mN. The experiment is conducted by vibrating the ERAU test bed, at varying amplitudes and frequency and the respective resultant forces acting on the cylinder wall are calculated using load cells and DAQ. The stiffness that in turn develops in the membrane due to the applied electromagnetic force is neglected in this experiment. Computational finite element analysis of the same also has been performed and these results have been compared and validated with the experimental results. It can be concluded that the given electromagnetic field gradient is effective in controlling the low slosh amplitudes. However, the time taken by the existing magnet to dampen the vibrations, in the case of higher slosh amplitudes, is found to be considerably high. An electromagnet with higher electromagnetic field gradient is thereby needed.

V. Acknowledgements

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VI. Future Work

To maintain the constant and effective magnetic field gradient across the cylinder, Helmholtz coils must be used instead of electromagnets. Helmholtz coils can also be used to steer/position the membrane at the desired height inside the cylinder. Membrane should be made by higher stiffness material to produce effective damping. The stiffness that in turn develops in the membrane due to the applied electromagnetic force will be investigated.

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