Slosh Damping with Floating Electro-active Micro-baffles

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Liquid sloshing within propellant tanks of launch vehicles and other major vehicles has been a major concern. Various methods have been utilized for the damping of slosh through Propellant Management Devices (PMD) accomplishing a wide range of results. Exploratory research conducted at the Embry-Riddle Aeronautical University Fuel Slosh Test Facility in development of an innovative PMD is presented. Embedding floating micro-baffles with an electro-active material such that the baffle can be manipulated when exposed to a magnetic field preserves the benefits of both floating and static baffle designs. Activated micro-baffles form a rigid layer at the free surface and provide a restriction of the fluid motion. Proposed micro-baffle design and magnetic activation source method along with proof-of-concept experiments comparing the scope of this research to previous PMD methods are presented. A computational fluid dynamics approach is outlined. Preliminary proof-of-concept testing indicates floating electro-active micro-baffles reduce the damping time of sloshing by up to 88% as compared to the same slosh condition with the absence of any PMDs.

Nomenclature

\begin{align*}
A &= \text{amplitude of oscillation} \\
\omega &= \text{frequency of oscillation} \\
t &= \text{time of simulation} \\
t_0 &= \text{initial time} \\
F_x &= \text{force in the x direction} \\
N_c &= \text{number of actuation cycles} \\
p &= \text{pole strength} \\
A &= \text{core cross-sectional area} \\
I &= \text{magnet wire current} \\
N &= \text{number of turns}
\end{align*}

I. Introduction

The presence of liquid in a tank which is exposed to dynamic conditions has been under review for quite some time. Such scenarios may occur in liquid propellant rockets, aircraft propellant tanks, ships, petroleum tankers, and other applications. Sloshing of a liquid can cause the tank system to deviate due to the buildup of kinetic energy of the liquid and its consequent interaction to the walls of the container.\textsuperscript{1} Fluid sloshing is defined as the periodic motion of fluid with the free surface in a liquid container. The hydrodynamic forces exerted due to sloshing pose a risk to the structural integrity of the tank walls.\textsuperscript{2} This concern is augmented with the constantly increasing size of space vehicles and rocket vehicle propellant containers and the significant dynamic forces they are exposed to.\textsuperscript{3} For this reason, propellant management devices (PMD) are not a new domain of the engineering world.

Through the years, various techniques to dampen the motion of the liquid propellant have come into existence and such techniques involve passive structural devices and active mechanisms.\textsuperscript{4} A diaphragm is a type of passive PMD that is implemented within the propellant tank itself. As the liquid propellant leaves the tank, the diaphragm compresses and lessens the amount of surface area in which the liquid would originally slosh. A baffle is a similar

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type of passive PMD that creates a simple barrier that acts to restrict the physical motion of the liquid thus damping
the amount of slosh it can exhibit. The two main types of baffles are wall-fixed and floating; each accompanied by
their own set of advantages and disadvantages. The primary advantage of floating baffles is the reduced weight over
their wall-fixed counterparts. Additionally, wall-fixed baffles are limited in their placement with respect to the tank
walls due to the presence of supporting structures which may be located on the tank walls.

Active damping mechanisms physically create waves that destructively interfere with the liquid propellant
undergoing sloshing. By changing the frequency at which these waves are created, the magnitude of the sloshing
waves can be controlled. Should the operating frequency of the mechanism coincide with the resonant frequency of
the propellant, the sloshing waves of the propellant would be completely damped instantaneously. Unlike the
passive PMDs, this mechanism has never been implemented into an operating space system. Some of the designs
include mounting baffles of various shapes to the inner sidewall of the tank.

Previous research of slosh suppression via floating baffles has indicated that successful damping of fluid slosh is
based on the same principle; baffle members interact by colliding with one another thus absorbing the kinetic energy
impacted to the fuel upon movement of the tank. Other baffle methods are defined as successful by increasing the
natural frequency of the tank sections and decreasing the wave amplitude at the free surface. A study on the
analysis of boundary element models for liquid sloshing concludes that the effect of the baffle position on the slosh
reduction is more important than the geometry and location of the baffle especially if the baffles are appropriately
located near the free surface.

The concept of floating electro-active micro-baffles is adapted from previous research involving the constrained
floating baffle, and also the use of a diaphragm on the free surface. It provides a structural layer to constrain the
free surface of the liquid. Floating micro-baffles allow the damping of slosh at all filled levels of the tank and also
adapt to the attitude of the vehicle. Upon exposure to magnetic fields of varying strength, it is predicted that the
rigidity of the structural layer can adapt to various slosh conditions. Furthermore, this slosh suppression method
preserves the natural frequency increase and kinetic energy interactions that correspond to both wall-fixed and
floating baffle PMDs. The challenges encountered and the milestones achieved at this stage of the development of
floating electro-active micro-baffles; specifically in the development of the micro-baffle design, the magnetic
activation source, and proof-of-concept experiments are documented.

II. Research Objectives

The overall goal of this research is to create a semi rigid structural grid at the free surface of the liquid upon
activation of the floating electro-active micro baffles. The primary objective in achieving this goal is to determine a
suitable activation method. This may include, but is not limited to, orientation and strength of the magnetic source
which activates the baffles as desired. The secondary objective is to define parameters which characterize the
rigidity of the structural grid; namely the strength between magnetically bonded elements. At this point in the
research, efforts towards the primary and secondary objectives have focused on electromagnet design/assembly and
modifications to the baffle geometry and electro-active material. The approaches taken towards primary and
secondary objective efforts are separately discussed in this report and directly related to preliminary proof of concept
experimental results.

III. Methodology

The objective of this paper is to provide conceptual validation of floating electro-active micro-baffles for the
purpose of slosh damping by computational fluid dynamics (CFD) analysis and experimental analysis. The
computational approach provides a comparative simulation of the slosh. The experimental approach provides a
realistic visualization of the problem and helps to define the modeling after using CFD.

A. Experimental Approach

1. Experimental Setup

The current experimental setup portrayed in Fig. 1 consists of a dynamic force-balance, fixed to an Aerotech
single axis linear motion actuator. Sloshing is generated in a lateral direction by providing a mechanical frequency
of given amplitude. The tank is held by arms linked to Futek dynamic load cells to measure the forces acting on the
walls of the tank. The setup is equipped with an adjustable rotary scroll which can to accommodate a variety of tank
sizes ranging from 8” to 16” in diameter. Experiments outlined in the scope of this report are conducted using an 8”
tank.
The actuation is programmed by Aerotech’s Soloist CP Software, which receives control from a unique LabVIEW Code developed at Embry Riddle Aeronautical University (ERAU). The load cells resolve the forces and moments on the sidewalls of the tank into the radial, tangential and vertical directions. For the purpose of proof of concept, only the two load cells which record the maximum reaction forces and moments due to actuation have been used. The National Instruments myDAQ is used in conjunction with a custom built signal conditioner to acquire the data signals from the load cells. Output force and moment is later imported into a MATLAB code to plot final results.

![Figure 1. (a) Tank assembly and Aerotech linear actuator with Futek load cells close-up and (b) Tank setup equipped with magnetic activation source.](image)

The tank as shown in Fig. 1 (b) is filled with propellant 60% by volume, which has been identified through experimental testing to induce maximum slosh amplitude. The testing fluid is water instead of common rocket propellant, hydrazine, because they are physically similar. The tank is open at the top for ease of access and to place the magnetic activation source and micro-baffles.

The experimental testing is conducted in three phases. The first phase characterizes baseline sloshing values for the fluid within the tank, i.e. free sloshing. The second phase repeats the experiment to evaluate the degree of damping present due to inactive micro-baffles floating on the free surface. The floating micro-baffles will be activated during peak sloshing in the third phase of testing. Each of the three phases will be repeated for two test cases; ‘low’ sloshing and ‘high’ sloshing. Low sloshing corresponds to a condition such that the slosh waves reach a height that is 12.5% of the tank diameter. Similarly, high sloshing waves reach a height that is 25.0% of the tank diameter. Table I below outlines the parameters used for each test case.

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Amplitude, A (mm)</th>
<th>Frequency, $f_n$ (Hz)</th>
<th>Cycles, $N_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Sloshing</td>
<td>2.3</td>
<td>2.0</td>
<td>10</td>
</tr>
<tr>
<td>High Sloshing</td>
<td>3.1</td>
<td>2.0</td>
<td>10</td>
</tr>
</tbody>
</table>

Testing for both phases is started by generating the sloshing laterally until a natural frequency is reached, i.e. the peak of its sloshing activity. The agitation of the tank is then stopped to allow natural damping to occur. This is allowed for a period of time in order to achieve complete damping.

Load cell output signals are refined using a low pass filter (LPF). The damping effect is characterized by evaluating the signal immediately after the point in time where actuation of the Aerotech system has ceased. LPF signals and damping times between each of the testing phases are compared.
2. Electro-Active Micro Baffles

Extensive iterations in the geometry of the micro-baffle design and electro-active agent have been conducted. Modification of the type and amount of electro-active material embedded within the chamber has a direct effect on the required buoyancy to keep the baffle afloat. A CATIA model of the most current electro-active micro-baffle revision is illustrated in Fig. 2.

The current design is a triangular base-lid shape printed from Acrylonitrile Butadiene Styrene (ABS) plastic and Polylactic Acid (PLA) plastic with 1.5" long sides and 0.4" thick with an inner structure of two components; an air chamber for added buoyancy and a channel 0.075" wide along the perimeter to house the electro-active material. While other cross sectional shapes had been considered for the experiment, an array of equilateral triangles showed to be the most viable option for this particular experiment. ABS and PLA plastics are both relatively light and buoyant, which are important parameters for this experiment. Upon locating the electro-active material into the inner channel the lid is secured using PVC cement.

Initially, baffles are filled with various mixture solutions of Carbonyl Iron (CI) particles and ferrofluid. As research efforts progressed and more is learned about the interaction between adjacent activated baffles and the magnetic source, it is concluded that the electro-active material embedded within the baffle structure needs to be one that preserves the magnetic flux which is transmitted through the baffles. That is, a material that is as magnetically permeable as possible. This conclusion is realized when two adjacent baffles filled with just CI particles forms a stronger bond than adjacent baffles filled with just ferrofluid. This concept is illustrated in Fig. 3. Adjacent baffles embedded solely with CI particles are capable of withstanding an inertial load as opposed to their ferrofluid counterparts.

![Image](Figure 2. Micro-baffle base (left) and lid (right) 3D models.)

![Image](Figure 3. Comparison of magnetic bond between activated baffles with Carbonyl Iron particles (left) and ferrofluid (right))

Magnetic permeability is defined as a measure of the ability of a substance to sustain a magnetic field. With the exception of several man-made alloys and other magnetic mediums, raw iron offers the highest permeability value. Table II lists relative permeability values for a variety of materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative Permeability</th>
<th>Material</th>
<th>Relative Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>~1.0</td>
<td>Aluminum</td>
<td>~1.0</td>
</tr>
<tr>
<td>Stainless Steel (martensitic, hardened)</td>
<td>40-95</td>
<td>Stainless Steel (martensitic, annealed)</td>
<td>750-950</td>
</tr>
<tr>
<td>Iron (various)</td>
<td>5,000-200,000</td>
<td>Metglas</td>
<td>1,000,000</td>
</tr>
</tbody>
</table>

At this point in the research, steel nails offer a cost-effective and readily available solution and are being used as the electro-active material located within the micro-baffle channels. Printed baffles can be seen in Fig. 4.

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3. Magnetic Activation Source

Throughout the course of the research, modified solenoids, electromagnets assembled in the ERAU Fuel Slosh Test Facility, and bar magnets have been used to assess necessary requirements for the magnetic activation source. The source must be designed such that the flux lines emanate far from the pole of the magnet through the diameter of the tank. Therefore, a simple test setup as seen in Fig. 5, is devised which moves the magnetic source in proximity of an electro-active baffle floating in a cup of water to quantify the “influence range”.

The governing equation for the pole strength, in Tesla, of an electromagnet is equal to\(^\text{12}\):

\[
P = \frac{N \times I \times A}{L}
\]

Where \(N\) is the number of turns, \(I\) is the current, \(A\) is the cross-sectional area of the core and \(L\) is the length of the core.

When initial electromagnet assembly attempts and solenoid purchases proved unsuccessful in obtaining a suitable magnetic source, Eq. 1 is used in conjunction with the results of the influence range experiment to build a strong electromagnet. The product of this effort can be seen in Fig. 5.

This electromagnet is the current electromagnet used for all slosh tests and is made from 600 ft. of 18 gauge wire, and a 0.75” steel pipe fitting core, 1.5” long. Conduit plates are used as end caps and a 0.75” thick steel bolt is filed to fit into the pipe fitting after the wire is wound. The 18 gauge wire used for the electromagnet has a cross sectional area of 0.823 square inches and maximum current of 2.3 amperes.\(^\text{13}\)

Compared to the 6.5 cm influence range of the most effective solenoid, the current electromagnet has an influence range of \(\sim 20.0\) cm.

![Figure 4. Micro-baffles mid-production with 1.25” long 0.075” diameter nails (left) and activated micro-baffles (right).](image1)

![Figure 5. Solenoid influence range experimental setup and magnetic activation source fabricated (corner).](image2)
B. Computational Approach

The CFD analysis of the slosh damping system using micro-baffles is categorized as a Fluid-Structure Interaction (FSI) with Electromagnetism problem. FSI problems and multiphysics problems in general are often too complex to solve analytically and so they should be analyzed by means of experimentation or numerical simulation. Research in the fields of computational fluid dynamics is still ongoing but the maturity of this field enables numerical simulation of FSI. Two main approaches exist for the simulation of FSI problems: a monolithic approach where the equations governing the flow and the displacement of the structure are solved simultaneously using a single solver. The other is the partitioned approach where the equations governing the flow and the displacement of the structure are solved separately with two distinct solvers. The ANSYS CFX solver is commonly utilized to produce an FSI fuel slosh solution by coupling ANSYS CFX and ANSYS Mechanical solvers. Forces exerted on any structural layer due to sloshing interact nonlinearly.

The most important parameter defined in this setup is the type of analysis being performed on the tank. ANSYS allows users to model the system globally using the ANSYS Workbench module. The micro-baffle structural component is setup using ANSYS Mechanical by isolating the structural domain from fluid in the system geometry and identifying boundary conditions.

The tank utilized in this simulation is designed with the same dimensions as the experimental tank so that an accurate comparison can be made to the experimental simulations. The tank is set to act as the outer structural boundary of the system. For simplicity purposes, the tank is modeled as a thin walled cylinder. The FSI system, like all subsequent tank models, is defined as a transient analysis because it is assumed that the behavior of the fluid is ever-changing with respect to time. The total simulation time is also carefully chosen so that the solution to the fuel slosh model is allowed to build in time and produce acceptable results. The simulation is programmed with a user-defined function to “excite” the propellant tank model at a particular frequency for a predetermined amount of time. As the tank oscillates about a single axis, the computational solver is recording the desired outputs of the particular test. For this simulation, the tanks are excited for 10 seconds before stopping, allowing the fluid to dampen for an additional period of time. Three simulations will be executed to match the three phases previously outlined in the experimental approach.

The Phase I simulation includes an 8” diameter tank modeled using CATIA V5 and imported to the ANSYS Workbench Design Modeler and ANSYS Meshing tool. The model is meshed to a patch conforming method with a face sizing near the fluid surface to obtain the following mesh parameters; number of nodes - 33,000 and number of elements - 148,000.

The setup of the CFX model is carried out by importing the mesh from the workflow. The walls of the cylinder are set to a wall condition with a specified displacement, in inches, along the X axis using a CFX expression that is defined by the following function:

\[ A \times \sin(2\pi f_n t) \times \text{step}(t_0 - t) \]  

\( (2) \)
These wall conditions with the specified displacement are also applied at the bottom of the cylinder. The fluid within the vessel is set up using the Volume-Of-Fraction (VOF) method to vary the fluid volume height of the tank with respect to the time of the simulation. The analysis type is set as Transient, to run for ten seconds at a time step of 0.001 seconds. Similarly, the Phase II simulation imports CATIA models to the ANSYS workbench Design Modeler and ANSYS Meshing tool. The Phase II mesh would be a lot finer around the region of the baffles. A patch independent mesh is recommended.

The setup for this phase adapts a rigid body problem to simulate the bodies of the baffles to float on the fluid surface. The rigid body coordinates are set to the individual baffles, and their corresponding rigid body properties are set. Rigid body problems require a high quality mesh that yields a very high number of elements and a low required time step during simulation. This hence results in a longer simulation time.

Due to the computational complexity of simulating a Fluid-Structure Interaction rigid body problem with an electromagnetic field, the electromagnetic field is not included in the Phase III simulation. Instead it is assumed that the baffles would remain stationary due to the formation of a semi-rigid grid. Hence it is set as a wall in the CFX Pre-Post. Results from the simulations are obtained from the force response plots generated from the combination of the Multiphysics solvers. By default, ANSYS monitors display the force and moment responses within the cells of the domains for the duration of the simulation. The results of the simulations are not included in this paper.

IV. Results and Discussion

A. Experimental Results

The LPF analysis method serves as a visual inspection and comparison of the sloshing and inherent damping present between each test. Fig. 8 displays a sample load cell output signal for the free slosh. The force signal consists of two halves; the output corresponding to the linear actuation and the remnant sloshing after the actuation has terminated.

The amount of damping present is characterized by the time it takes the remnant sloshing to dissipate and return to equilibrium. This value is indicated on Fig. 8 below. For the purpose of comparison, the damping time is referred to as the time it takes for the remnant sloshing peak-to-peak amplitude to reduce to half its initial magnitude. There exists a noise signal that appears on an average of every four seconds. It is predicted that the source of this noise would be from background sources from the laboratory in which the experiments are conducted. Upon the application of a Low Pass Filter these noise signals are only partially eliminated. Figures 9 through 14 compare the force output that was recorded for all six test iterations as remnant sloshing is dissipated.

![Figure 8. Sample free-slosh force signal with example half damping time.](image)

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Figure 9. Phase I - Low Slosh Force Signal

Figure 10. Phase I - High Slosh Force Signal

Figure 11. Phase II - Low Slosh Force Signal

Figure 12. Phase II - High Slosh Force Signal

Figure 13. Phase II - Low Slosh Force Signal

Figure 14. Phase III - High Slosh Force Signal
Visually, the activated baffle tests indicate a quicker damping time over the inactive baffle and free-slosh tests. Table III quantifies the damping times, $t_d$, for each test iteration.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Test Case</th>
<th>$t_d$ (s)</th>
<th>% difference to free-slosh condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I</td>
<td>Low</td>
<td>5.7</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>10.9</td>
<td>N/A</td>
</tr>
<tr>
<td>Phase II</td>
<td>Low</td>
<td>5.1</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>5.5</td>
<td>49.5</td>
</tr>
<tr>
<td>Phase III</td>
<td>Low</td>
<td>1.5</td>
<td>73.7</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>1.3</td>
<td>88.1</td>
</tr>
</tbody>
</table>

Considering the fact that the activated baffles induce up to 88% reduction to the damping time of the free-slosh test case, electro-active floating micro-baffles are a suitable PMD for the scope of this experimental setup. The reaction moment signal does not provide as clear of a representation of the force signal.

V. Conclusions and Future Work

The various electromagnets are assembled and tested to provide a fairly strong magnetic field. In addition, a preferred model of the micro-baffle is designed and tested for buoyancy and efficiency in grid formation. The most suitable combination of electromagnet is used in the slosh tests and the filtered results are plotted and compared. A favorable trend in the results is achieved for experiments with the electro-active baffles by noting that there is a prominent reduction in the damping time of up to 88% hence proving the concept of floating electro-active micro-baffles as a viable slosh damping mechanism. Numerous complications and limitations faced during CFD simulation provide the need for more effective computer resources.

Though floating electro-active micro-baffles offer a significant increase to slosh damping over inactive floating baffles, the scope of the experimentation has been limited. A number of issues need to be addressed and further experimentation must be conducted. Most importantly, the efficiency of floating electro-active micro-baffles must be further compared to previously developed PMDs such as diaphragms and wall-fixed baffles. Representation of actual slosh conditions would bolster the effect of the experimental results. At this point in the research, the main challenges are due to the micro-baffle design, magnetic activation source, and the interaction between both elements. Usage of a more magnetically permeable electro active material such as Metglas is to be investigated. Revision to the inner structure geometry and overall shape of the baffle should also be considered. As research progresses, a more consistent method of manufacturing the baffle will be incorporated. Upon refinement of the micro-baffle design, the magnetic activation source will have to be revised. In addition to relating the strength of the magnetic pole to baffle interactions, different magnetic source configurations will be considered with an emphasis of implementing an electromagnet that adjusts to the change in free surface height.

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References