History of Fuel Sloshing

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Fuel sloshing in propellant tanks can present significant problems for any spacecraft propulsion and attitude control subsystems. Modeling the behavior of the fuel inside the tanks from the ground to the target orbit is crucial for mission success. If a spacecraft is orbiting in unaccelerated flight and is about to perform an orbit maneuver or correction burn, the fuel in the propellant tank may not be ideally positioned to feed into the combustion chamber and engine failure can occur. This paper is an overview of the history of fuel sloshing and how solutions to this problem have evolved with the advances in rocket technology. By combining experimental and CFD simulation data, engineers can model the behavior of the fuel inside propellant tanks and implement measures to avoid harmful fuel sloshing or boil-off, especially when performing any engine burns. The use of anti-slosh baffles within tanks and ullage motors are some of the active measures to combat the adverse effects of fuel sloshing. Spacecraft must also be equipped with an attitude control system that is compatible with the fluid dynamics of its propellant tanks so that the reaction control thrusters can counteract any disturbances to the spacecraft's orientation from fuel sloshing. Some examples of current and past experiments that explore this problem are included in this paper to provide key insight into the fuel sloshing problem.

I. Nomenclature

ACS = *Attitude Control System*
CFD = *Computational Fluid Dynamics*
CFE = *Capillary Flow Experiment*
FARE = *Fluid Acquisition and Resupply Experiment*
FLEVO = *Facility for Liquid Experimentation and Verification in Orbit*
JWST = *James Webb Space Telescope*
LAD = *Liquid Acquisition Devices*
PMD = *Propellant Management Devices*
SPHERES = *Synchronized Position Hold, Engage, Reorient, Experimental Satellites*
VTRE = *Vented Tank Resupply Experiment*

II. Introduction

In March 1926 when Robbert Goddard achieved the launch of the first liquid-fueled rocket, the floodgates were open to a world of discovery and innovation in space exploration and rocket technology[2]. The fact that Mr. Goddard built a rocket-propelled by mixing a fuel source and an oxidizer was groundbreaking, and liquid propulsion systems started to evolve rapidly but not without a corresponding increase in complexity. As we strive to push the boundary of human capabilities, return to the Moon, and venture out to Mars, understanding how to maximize and accurately predict the performance of our spacecraft propulsion systems is of utmost priority. Fuel sloshing is the periodic motion of the fuel inside its container which can be caused by changes in the movement and acceleration of a spacecraft or vehicle. The effect of sloshing inside the fuel tanks can be compounded if the vehicle experiences any external disturbances with frequencies that approach the sloshing frequency of the fluid [1]. The fuel carried by rockets and airplanes composes a large percentage of their overall weight. Therefore, the effects of uncontrolled and violent fuel sloshing inside the tanks of these vehicles will create disturbances that cannot be ignored without sacrificing the safety and success of the vehicle and its mission. Fluid mechanics is a very rich discipline and research to model the behavior of fluids actively takes place in a multitude of industries. While it is true that the anatomy of the tanks of a fuel truck will be different from that of a spacecraft, the physics and dynamics of the fuel sloshing apply to both equally. In the

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[2] Credit: NASA/Brian Dunbar URL: https://www.nasa.gov/missions/research/f_goddard.html.

realm of aeronautics and astronautics, researchers and engineers strive to develop systems that model the behavior of liquids when subjected to Earth's gravity field and in a microgravity environment. By combining the knowledge gained from simulation and experimental results, we can develop safer and more efficient fuel tanks and PMDs that will help to enable long-duration missions, establish orbiting fuel depots, and push the limits of space exploration.

III. Physics of Fuel Sloshing

When a rocket lifts off from the surface of the Earth, it is carrying a very high percentage of its initial weight as fuel. Under the extreme acceleration of launch, the fuel and oxidizer are conveniently guided toward the bottom of each of their tanks where they can be pumped into the engine to continue the combustion process. In these conditions, the propellant subsystems of fuel acquisition and gauging have an easier task because there is a clear boundary between the liquid and gas in each tank. The fuel sloshing phenomenon can be described as having an amplitude and a frequency and it depends on multiple variables like the Bond number, viscosity, fuel fill level, and the geometry of the tank [2]. The Bond number is dimensionless, describing the ratio of gravitational forces to surface tension forces. On the surface of the Earth, the behavior of liquids is mostly dominated by viscous and gravitational forces, therefore corresponding to a high bond number. In a microgravity environment, such as the International Space Station (ISS), a liquid will behave differently because surface tension forces dominate in these conditions. Because fluids behave differently depending on the environment they are in, different PMDs may be utilized for each rocket stage since the fuel behavior will depend on the conditions under which the rocket is operating. As aforementioned, during the launch, the fuel is assisted by gravity and the acceleration of the rocket to settle on the bottom of the tanks and be pumped into the engines to sustain propulsion. Once the first stage is expended and separated, the rocket's second stage ignites, raises the vehicle to the desired altitude, and establishes an orbit. When this second or third-stage engine shuts down for the first time, the fuel tanks will be at a lower fill level than when the burn started, and the propellant will start sloshing around because of the engine shutdown event. Newton's first law of motion describing inertia is a nice explanation for why the fuel sloshes after engine shutdown. However, the dynamics of the fuel inside a tank under microgravity conditions differ from the initial launch conditions. Because surface tension forces dominate the behavior of liquids in the microgravity realm, engineers had to figure out a way to separate all the liquid and gas inside the tank and stop any sloshing before another engine burn can occur. As can be seen in Figure 1, liquids tend to stick to the walls of the container, and this is another problem that must be addressed when designing fuel tanks to operate in microgravity or deep space. Section IV discusses PMDs like sponges and vanes that allow the spacecraft to control the fuel inside its tanks. Another consideration for fuel in microgravity is the possibility of a boil-off event when fuel encounters the walls of the tank if these are not protected from thermal radiation. A historical example of fuel sloshing disturbances occurred in the Apollo program. During the Apollo 11 mission, there were some deviations in the orientation of the lunar module due to propellant sloshing. With fuel levels reaching about 50%, the sloshing inside the tanks after a yaw maneuver was enough to make the spacecraft oscillate 2 to 3 degrees from the desired orientation, meaning the reaction control thrusters had to actively correct this deviation[3]. The fuel sloshing inside those fuel tanks also triggered faulty sensor measurements that incorrectly reported the fuel levels in the tanks to be lower than they were.

Fig. 1 Slosh Experiment aboard ISS[4]

A damping factor also describes the system's overall response to the fuel sloshing and how quickly the fuel will return to a steady position. This damping factor is affected by variables like the tank geometry and other quantities that describe the fluid properties themselves. The damping factor of the fuel sloshing is usually determined experimentally by correlating trends in multiple sets of data for sloshing under different conditions. For example, in

[3] Credit: NASA/Eric M. Jones URL: https://history.nasa.gov/alsj/a11/a11.landing.html

[4] Credit: NASA, URL: https://www.nasa.gov/mission_pages/station/research/news/slosh_coating

1965, engineers at Ames Research Center were attempting to quantify a damping law that could be used to predict the damping of fuel sloshing in large tanks. The experiment was conducted in such a way that the formula obtained for the damping of the fuel sloshing could be used no matter the size of the tank, acceleration, or liquid density [4]. This parameter determination that describes sloshing behavior continues to be an important task for researchers. With the advancement of CFD software and experimentation techniques, more accurate models can be derived to describe the motion of fluids.

Furthermore, the stability of the airplane or spacecraft can be affected by fuel sloshing because the center of mass will shift with the motion of the fuel and unwanted moments can be imparted unto the vehicle. Using proper PMDs the spacecraft will retain its center of gravity within the accepted range with only slight changes as fuel is consumed. The JWST is especially susceptible to disturbances due to fuel sloshing after any pointing maneuvers are performed because it must maintain a steady attitude to accurately image its target [5]. Therefore, JWST needs to wait for the fuel to stop sloshing around and have its ACS active to maintain pointing accuracy. The ACS of JWST and other spacecraft must counteract and correct the disturbances that arise from sloshing, and it must do so in a manner that the small thrusting corrections will not amplify the fuel sloshing effect.

IV. Propellant Management Devices

PMDs are employed to ensure the fuel meets the appropriate requirements to be used by the propulsion system or other systems in a spacecraft. When the Earth's gravity field has a significant effect on the rocket during the first stages of launch, PMDs are generally not necessary because the acceleration of the rocket will maintain the fuel at the bottom of the tank, since it has a higher density than the gas, and prevent the mixing of fuel with the gas present in the tank. This is very important because the fuel pumps may be damaged and catastrophic effects on the propulsion system may occur if the fuel has some gas mixed into it. After the vehicle has entered the microgravity environment, PMDs are crucial to maintaining the fuel and vapor inside the tank separated so that the fuel can be easily fed into the combustion chamber [3]. Because of the changed dynamics of fluids in microgravity, the fuel will be in a state in which liquid and gas are mixed and this mixture cannot be fed into an engine without combustion instability or engine failure. PMDs are specially designed to maintain the liquid and gas separate within a fuel tank so the fuel can be transferred safely. All spacecraft that require liquid propellant employ one form or another of PMDs. We can already imagine more applications of PMDs for orbiting fuel depots that must ensure the fuel inside the storage tanks is separate from any other gas inside the tanks, and transfer fuel safely to a docked spacecraft. For long-range missions that may require multiple engine shutoffs and restarts, PMDs will play a crucial role in ensuring that the spacecraft can safely restart the engines as needed. The amount of fuel inside the tanks is also relevant to discuss because it will determine what PMD will be effective to separate the liquid fuel and gas inside the tank. Another engineering decision arrives when designing and selecting the appropriate PMD while minimizing the system mass and maintaining effectiveness.

Some examples of PMDs include diaphragms, bladders, baffles, sponges, vanes, and more [3]. The bladder is a device that resembles a balloon and holds the propellant inside its membrane, keeping it separate from any gas and preventing any flow in the bladder where the fuel is located [6]. A diaphragm comprises a flexible membrane that helps divide up the fuel and the vapor within the tanks [7], [8]. Figure 3 shows a diagram of a damping internal diaphragm used for the New Horizons and Deep Impact spacecraft[5]. These two PMDs must span across the entire tank and will add a significant amount of mass to the fuel tanks, therefore they are not the best options when the tank size starts scaling up. Baffles are different in the sense that they primarily dampen and reduce the fuel-sloshing inside the tank. Baffles are used in many fuel tanks across multiple industries varying in size and shape. Baffles might be less effective in microgravity environments because they won't be able to fully separate the liquid and vapor states, therefore they are mostly used in gravity-dominated environments. Sponges are open structures that can refill and maintain propellant separated and ready to be transferred to the propulsion system. Sponges are used to help with settling the fuel for engine restart and can also be used to control the propellant to maintain a specified center of gravity for the spacecraft. There is a larger list of PMDs used for different applications and missions with some of the devices like sponges being famous for their flight history and uses [9]. Vanes are another type of PMD that take advantage of capillary flow effects to control the fuel inside of the spacecraft's tanks. Figure 2 shows a PMD design that allows for the fuel to flow up the small openings in the vanes up to the fuel outlet that feeds the spacecraft's thrusters. Capillary effects describe how liquids can flow through narrow spaces like thin tubes because of a combination of surface tension within the liquid molecules themselves and adhesive forces between the liquid and the container walls. Some

[5] Credit: Southwest Research Institute/Grant Musgrove URL: https://www.swri.org/technology-today/stabilizing-force-fuel-sloshing

PMDs that take advantage of the capillary effects are vanes and sponges. Depending on the mission, engineers will compare the advantages and disadvantages of each PMD and select the one that best matches the design requirements and provides the required fuel management and control. An example of such a mission requirement can be a spacecraft needing a large fuel flow per unit of time into the engine for orbit maneuvers.

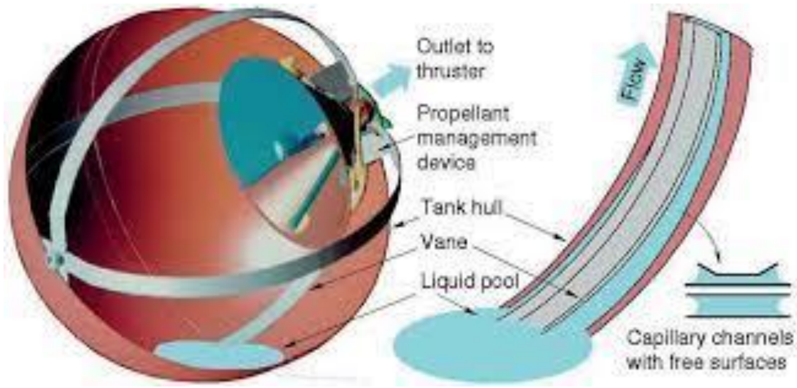

Fig. 2 Fuel tank capillary vanes design[6]

Fig. 3 Full-scale model of tank with internal diaphragm[7]

V. Experiments and Simulations

Research in the field of fuel sloshing for spacecraft applications dates to the 20th and does not seem to have slowed down to this day. Early models used to describe the physics of fuel sloshing were mechanical systems such as swinging pendulums or oscillating mass-spring systems[8]. While these systems provide quick approximations of the physics, they fail to accommodate other variables such as tank geometry, fill levels, viscosity, etc. With the advent of technology like advanced CFD software, researchers can create simulation models and pair the results of the computer analysis with other experimental results to predict the parameters and behavior of fuel sloshing more accurately. The simpler mechanical models mentioned can also be combined with CFD simulations to create realistic simulations of

[6] Credit: Przemyslaw Bronowicki, URL: https://cuvillier.de

[7] Credit: Southwest Research Institute, URL: https://www.swri.org/technology-today/stabilizing-force-fuel-sloshing

[8] Credit: Southwest Research Institute/Grant Musgrove URL: https://www.swri.org/technology-today/stabilizing-force-fuel-sloshing

fuel sloshing. Models of tanks with defined geometries and PMDs can be inputted into CFD software, yielding a faster and more efficient option for predicting the sloshing conditions inside a tank. This can be useful in the early stages of the design process, since it may not be feasible to create an experiment to test the exact sloshing conditions expected. For this type of scenario, CFD can be a great tool to advance along in the design process since the results from the computer analysis can always be validated with experimental data or higher fidelity simulations later in the design process [10]. In [11], CFD techniques were used to simulate the fuel sloshing inside a propellant tank with a diaphragm and the results obtained were consistent with the dynamics of sloshing. Multiple diaphragm geometries were also tested. The challenge in the simulation was adding the diaphragm feature into the tank geometry and accurately modeling its effect on the liquid.

Multiple fluid experiments have taken place aboard the ISS; one of those was called the SPHERES-Slosh experiment. In this experiment autonomous free-flying satellites known as SPHERES attached to a plastic tank and were able to conduct sloshing research to collect very valuable data. Sloshing experiments done in microgravity are crucial to understanding how the surface tension forces affect the fluid dynamics and the formation of bubbles when the fluid mixes with gas. The ISS also hosted another experiment named CFE where the behavior of capillary flows (movement of fluids in narrow spaces without external forces) and flows in containers with complicated geometries were studied[9]. These types of experiments are crucial to learning how to better control the flow of fluids in microgravity and provide foundational knowledge to be used in propellant tanks and fuel transport systems for future space vehicles. Also launched in 2005, Slosh Sat-FLEVO was a minisatellite aimed at studying the liquid of fluid dynamics and management in space. The satellite carried a tank with a volume of 86.9 liters and 33.5 liters of water.

Fig. 4 Astronaut Richard Mastracchio with SLOSH experiment[10]

With a multitude of sensors mounted on the tanks, it was able to observe the sloshing behavior and report back the data to the scientists and engineers at the European Space Agency. The spacecraft's operational life ended with a total of 57.5 experimental hours but its contributions to sloshing research were invaluable [12].

Launched aboard the Space Shuttle, the VTRE program was a NASA experiment aimed at expanding the knowledge of capillary vane flow and applications to fluid management devices [13]. The FARE experiments (shown in Figure 4) tested out different PMDs in a more rigorous way. Previously, the data available for the use of PMDs in orbit consisted of only the predicted and post-flight performance values of prior missions. This program was successful in demonstrating the capabilities of screen channel and vane-type PMDs that would then help create more analytical models for fluid management [14]. More recently, with the launch of the Artemis I mission, NASA and partner agencies conducted a small propellant slosh experiment with the Orion spacecraft by firing the reaction control thrusters and monitoring the effect the fuel sloshing on the spacecraft's trajectory and attitude[11]. Future research will continue adding layers of complexity to experimental and simulation setups so that the fluid dynamics in complex environments and conditions can be modeled to very high accuracies. The availability of high-fidelity simulation data

[9] Credit: NASA/Milton Weislogel/ISS Research Integration Office, URL: https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html?#id=951
[10] Credit: NASA URL: https://www.nasa.gov/content/slosh-fluid-capsule/
[11] Credit: NASA/Shaneequa Vereen URL: https://blogs.nasa.gov/artemis/category/orion-spacecraft/

will be a great resource for engineers designing spacecraft with varying mission profiles and will facilitate a growing pace of innovation.

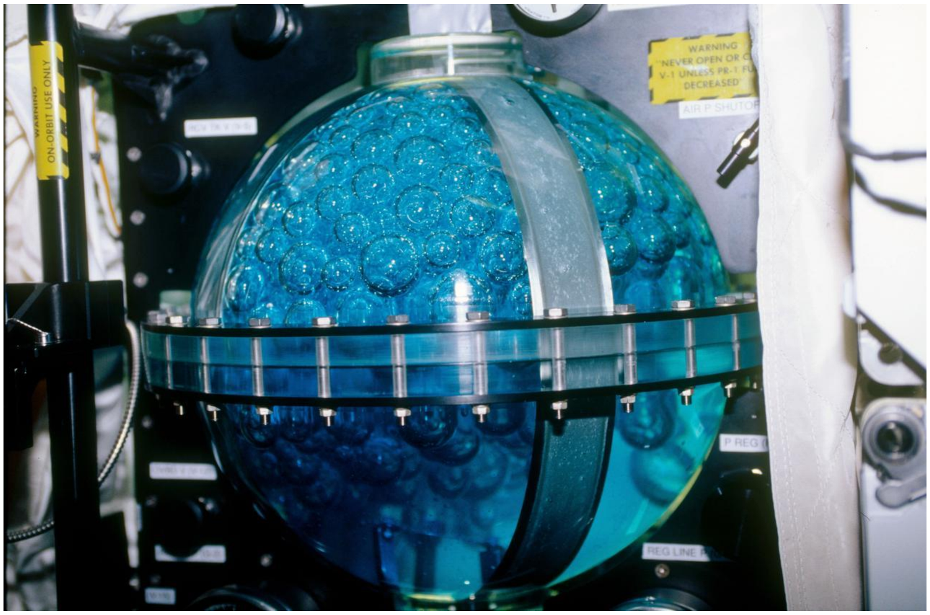

Fig. 5 FARE experiment aboard Space Shuttle Discovery[12]

VI. Conclusion

Fuel sloshing is a big part of any aerospace mission design and has evolving levels of complexity as the environment and other conditions change. The beauty in fluid dynamics is that some phenomena like sloshing can be observed in common day-to-day situations like rushing up the stairs with a filled coffee mug, and the same governing physics will also apply to the most complex of space missions. Efficient PMDs are highly critical for mission success and will be a part of the design process that goes through multiple iterations to arrive at a design that meets all the safety and performance requirements. Although fuel sloshing has been studied and researched for many years, especially under Earth's gravity, there is much more to learn about the behavior of fluids in microgravity and under a broader set of conditions. Modeling the fluid behavior accurately will serve as key knowledge for the design of long-term missions to Mars and beyond.

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[12] Credit: NASA/Johnson Space Center URL: https://images.nasa.gov/details/sts053-09-019

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