Advancing the Development of the Magneto-Active Slosh Control (MaSC) System for Spacecraft and Launch Vehicles

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Abstract

The Magneto-Active Propellant Management Device (MAPMD) system is designed to address safety hazards in liquid-propellant spaceflight caused by sloshing. This innovative system of Magneto-Active Slosh Control surpasses traditional passive slosh baffles by reducing mass, improving surface wave suppression, and minimizing volumetric intrusion (Santhanam 2012). In prior fight experiments conducted in collaboration between Embry-Riddle Aeronautical University and Carthage College, remnant slosh suppression was observed, however the effective slosh damping did not meet our expectations due to inadequate control forces. We are redesigning the magnetic membrane with multiple layers of ultrahigh-permeability metallic glass film and are developing an optimized configuration of current-carrying coils to increase magnetic force and field performance. These advancements are expected to elevate the MAPMD system's Technology Readiness Level (TRL) from 3 to 4 in order to pave the way for microgravity flight testing. The MAPMD system promises to enhance the safety and performance of liquid-propellant spaceflight by actively managing slosh dynamics.

Background

Unsettled liquids in liquid-propellant spaceflight exhibit a complex interplay of forces and motions, collectively referred to as "slosh," that presents substantial safety hazards. Slosh is characterized by the oscillatory movement of liquids, primarily driven by external accelerations and the fluid's inertia. The consequent shifting of the liquid's mass poses challenges, interfering with fuel consumption, transfer, and the overall stability and control of the spacecraft.

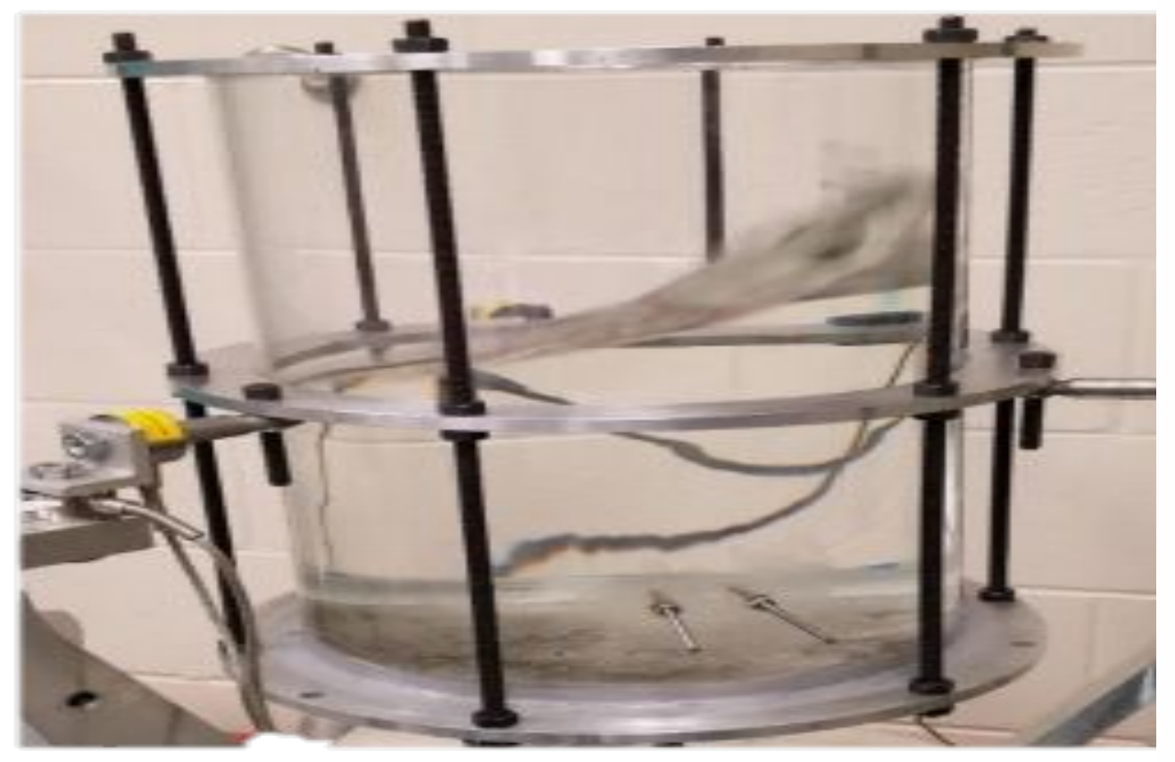


Figure 1: Slosh generated using Aerotech linear shaker (Subramanian et al. 2015)

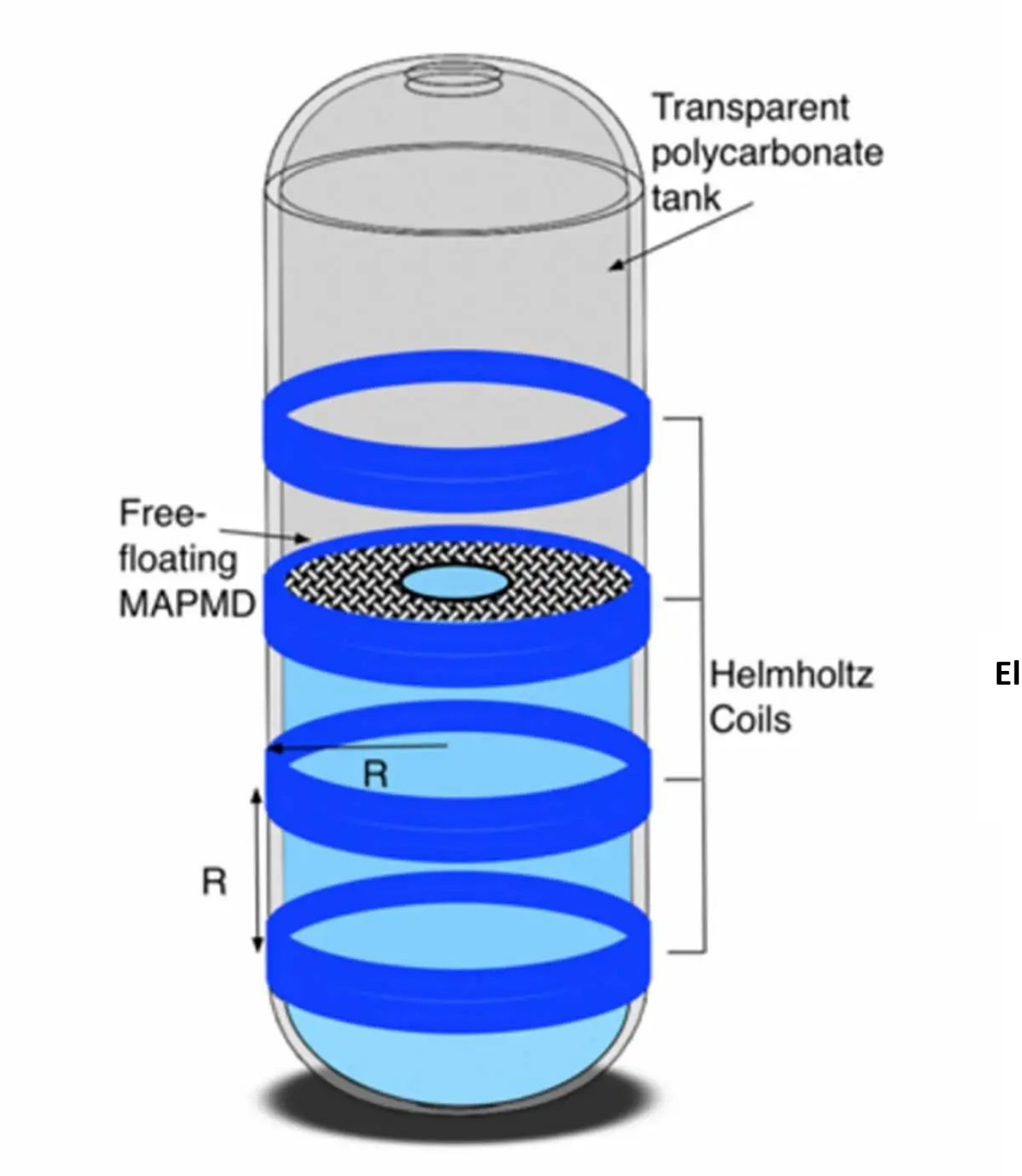


Figure 2: MAPMD System

The Biot-Savart Law describes that a current-carrying segment of wire generates a magnetic field proportional to the current moving through it, with field density inversely proportional to the squared distance from the source. Wound electromagnetic coils produce magnetic fields with axial symmetry (Nave). The magnetic field system is crucial for the MAPMD as it enables control over the Metglas material, facilitating its effective response to slosh-induced movements. Ampère's law governs this process, describing how a current-carrying conductor generates a magnetic field. An overlapping network of field-generating electromagnetic coils is used to control a magnetic membrane. Metglas boasts exceptional magnetic properties, including high permeability and low hysteresis loss. This material was chosen for its swift response to magnetic fields, allowing the membrane to adapt to liquid propellant slosh dynamics. This synergy between advanced materials and precise electromagnetic control enhances the MAPMD system's performance, ultimately bolstering the safety and efficiency of liquid-propellant spaceflight .

Modeling Methodology

Electromagnetic Principles and Equations:

Our methodology is grounded in the fundamental principles of electromagnetism, particularly as they relate to current-carrying coils and ferromagnetism. The magnetic field (B) at a field point of a distance z from the center of a current-carrying coil can be calculated using the Biot-Savart Law, where R is the coil radius, I is the current, n is the number of turns, and μ_0 is the permittivity of free space:

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I d\vec{l} \times (\vec{r} - \vec{r}')}{\|\vec{r} - \vec{r}'\|^2}$$

To calculate the applied force by the magnetic field on the magnetic membrane, we use the following formula for magnetic force due to an applied magnetic flux density (B-field), acting on a magnetic material with a magnetization M, inside a volume V, bounded by a surface S (see Jackson):

$$\vec{F} = -\int_V \left(\vec{\nabla}\cdot\vec{M}\right)\vec{B}\,dV + \int_S \left(\vec{M}\cdot\hat{n}\right)\vec{B}\,dS$$

Design Optimization and Trade Study:

In this project, a central goal is to enhance the force the magnetic field applies to a floating disc within the liquid propellant, essential for suppressing slosh in microgravity. Critical design variables to consider include the coil system's attributes such as number of coils, number of turns, coil radius, current, position, and orientation of each coil and additionally magnetic membrane's attributes, including the volume, surface area and shape of the magnetic membrane must be optimized to maximize the force equation above. Concurrently, the project aims to minimize the system's overall mass, a critical factor in spaceflight for efficiency and cost savings.

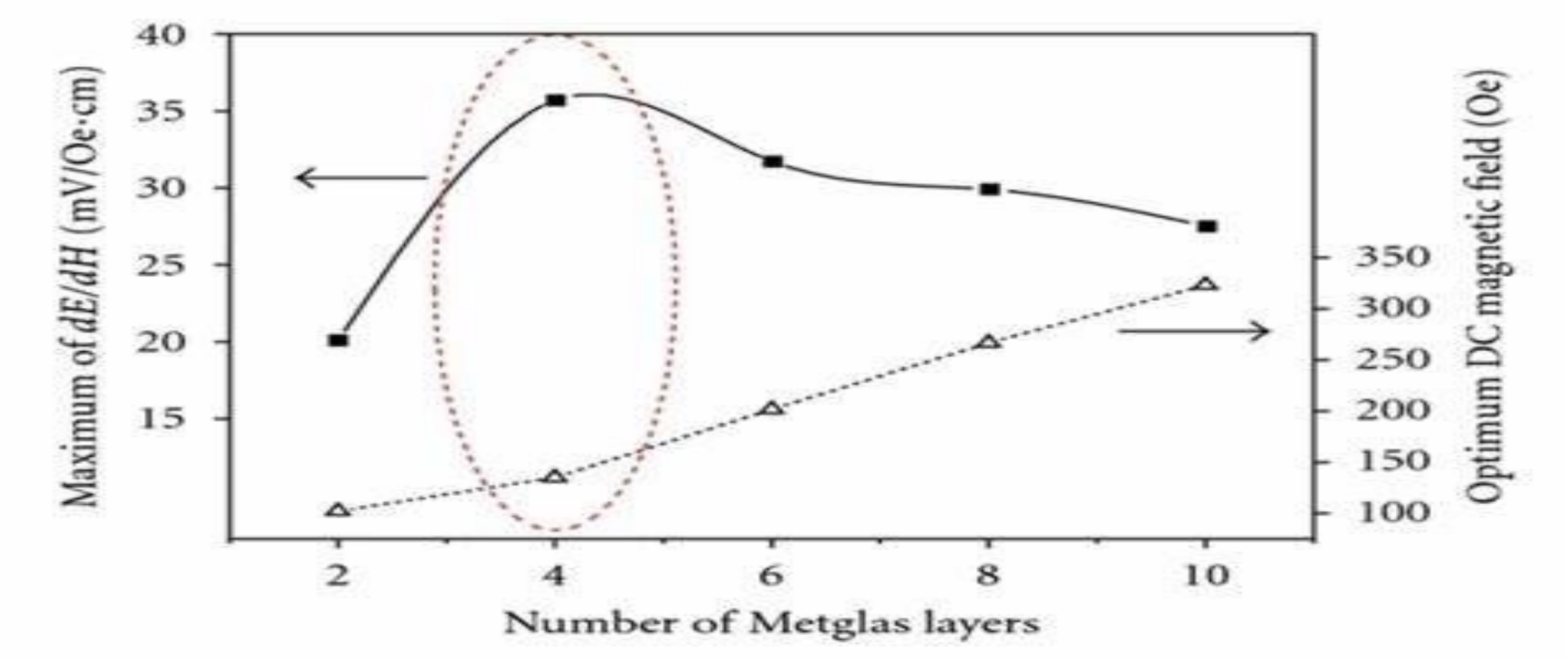


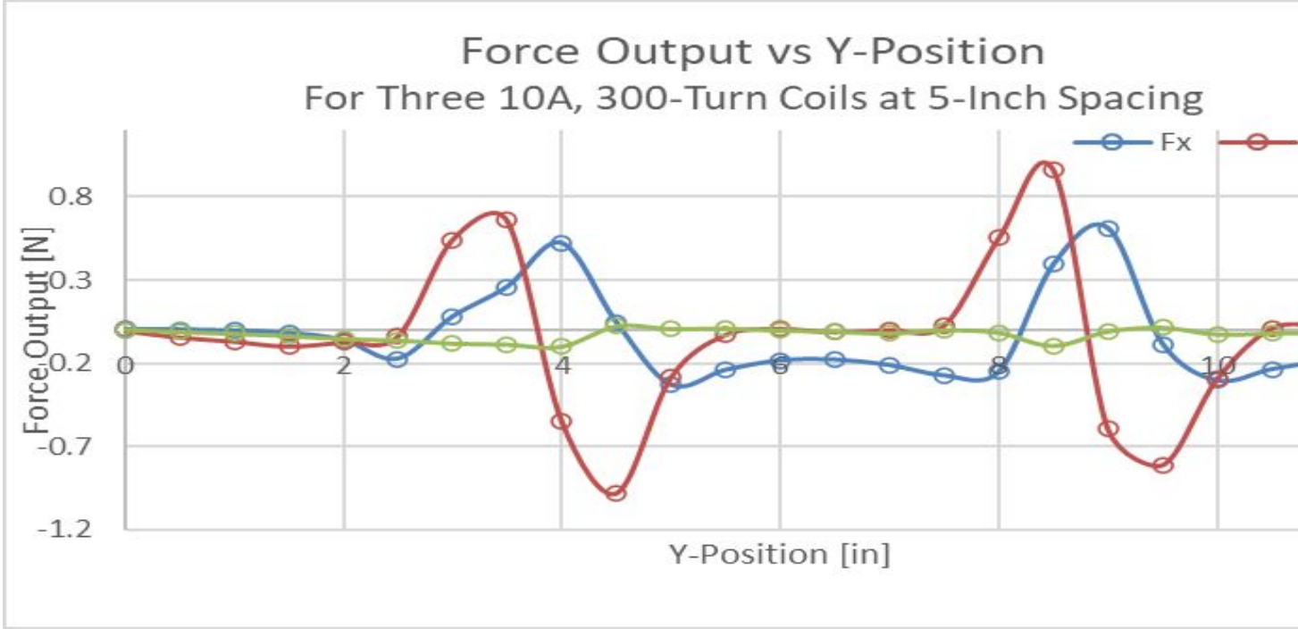
Figure 3: Optimization Chart for number of magnetic membrane layers and magnetic field strength.

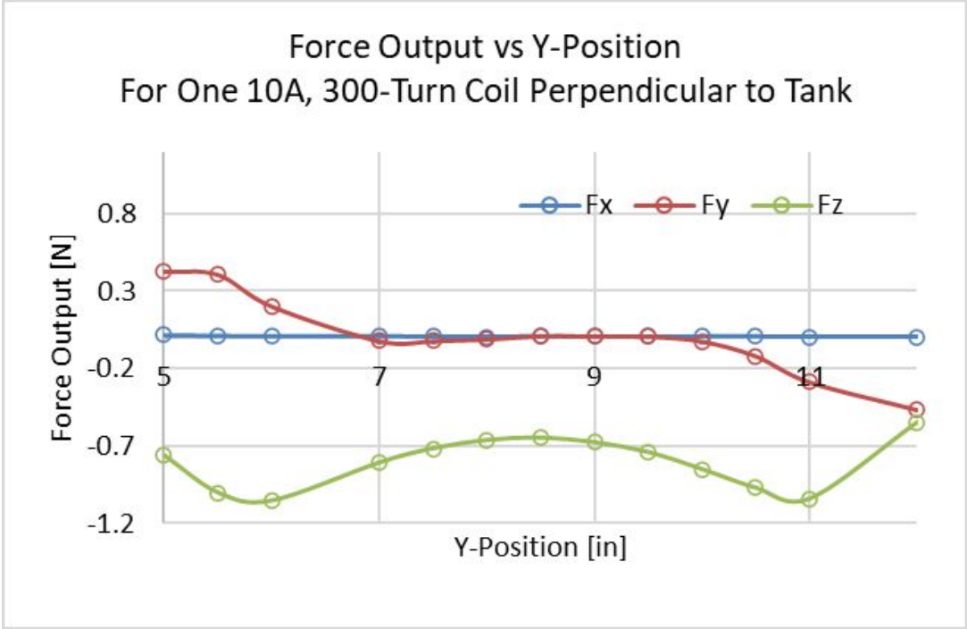
Software Modeling and Simulation:

For this project, simulation software is integral to exploring electromagnetism dynamics and optimizing design. EMWorks' EMS suite for Inventor is used to run parameterized force simulations. MATLAB, interfaced with the Finite Element Method Magnetics (FEMM) software, is employed to conduct electromagnetic simulations and assess the interactions within the system. Additionally, MATLAB's Optimization Toolbox is utilized, enabling a systematic exploration of the design space and facilitating the fine-tuning of design variables. This combination of software tools is essential in achieving an optimized balance between magnetic force maximization and mass minimization for increased likelihood of success.

Results and Discussion

Impact of Coil Placement on Force Field Distribution:





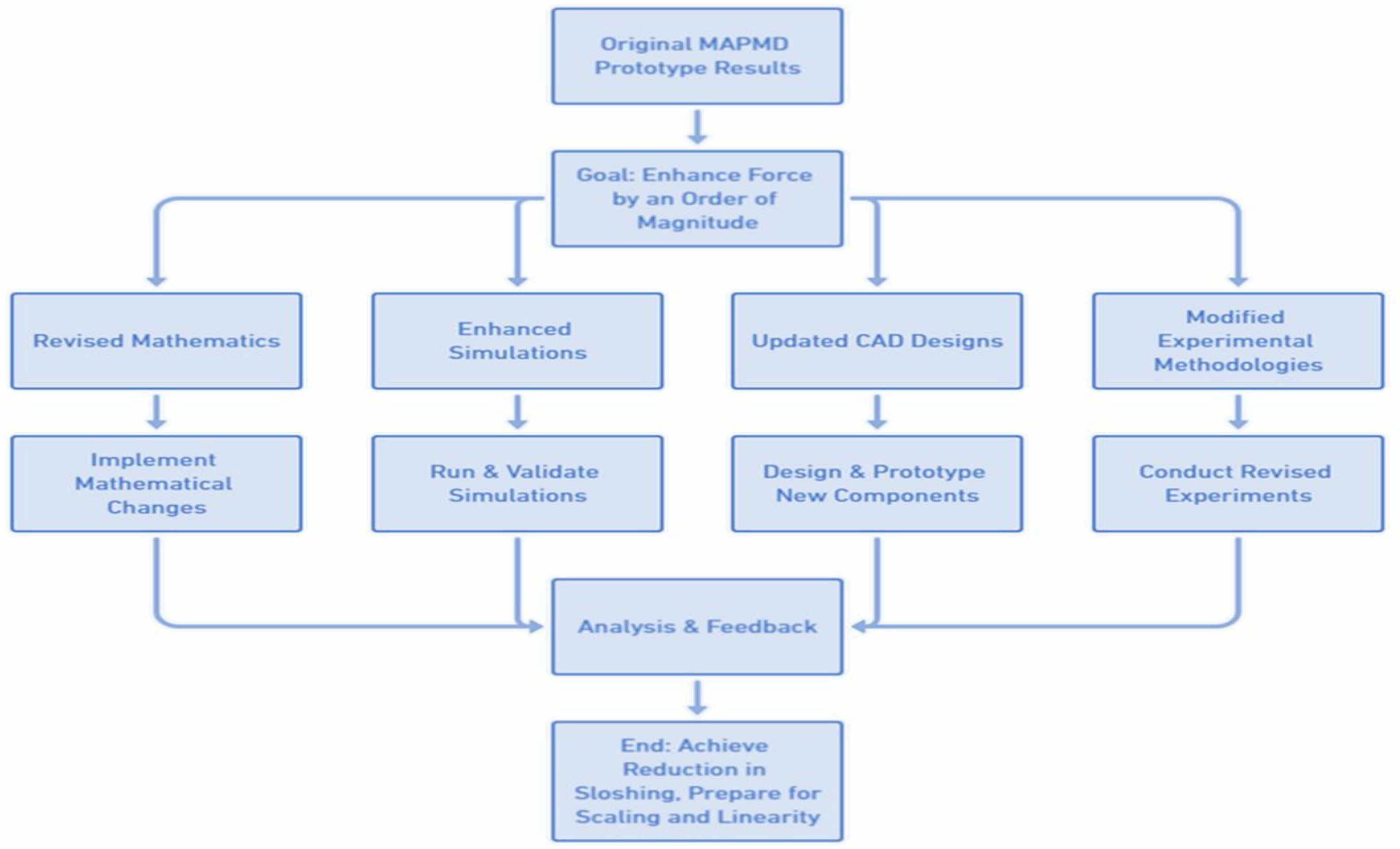
Interpretation and Evaluation of Key Findings:

To produce a larger force on the magnetic membrane, the magnetic field produced by the coil system needs to have a strong axial gradient. Helmholtz coils & other same-axis, 2-coil configurations are too uniform along most of the y-axis to provide adequate forces. We found that we must also increase the magnetic membrane thickness.

Challenges, Limitations, and Insights:

At present, magnetostatic simulations have been performed, however as the control system will change currents in the coils, they are expected to produce eddy currents, necessitating dynamic magnetic field and force simulations.

Future Direction:


Original MAPMD Prototype Results

Goal: Enhance Force by an Order of Magnitude

Revised Mathematics

Implement Mathematical Changes

Enhanced Simulations

Run & Validate Simulations

Updated CAD Designs

Design & Prototype New Components

Modified Experimental Methodologies

Conduct Revised Experiments

Analysis & Feedback

End: Achieve Reduction in Sloshing, Prepare for Scaling and Linearity

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Acknowledgements

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