

Voice Coil Assembly



Improved Robustness of Coriolis Flow Meters



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Background

Our Client - Emerson

Emerson is the premier manufacturer of Coriolis mass flow meters. **Our team was tasked with improving the robustness to shock loading of these meters**, which can occur in some applications. We redesigned the failure prone voice coil driver and sensor assemblies, providing inherent robustness without sacrificing the electromagnetic efficiencies needed for meter function and accuracy.



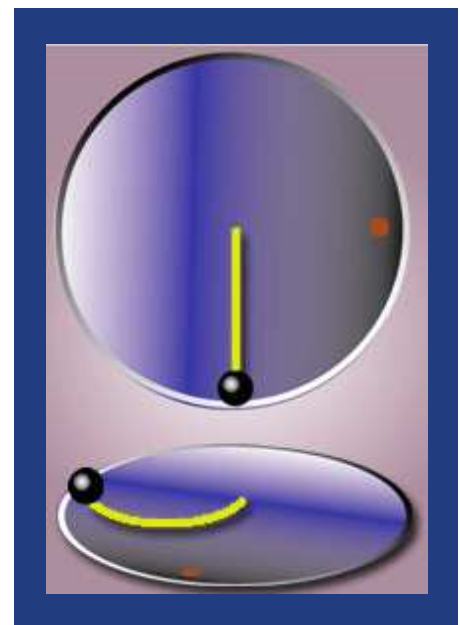
Flow Meters

The market for flow meters is rapidly growing with a projected valuation of \$11.9 billion by 2026. Flow meters serve a multitude of industries including Oil & Gas, Water & Wastewater and Food & Beverage. A large set of these flow meters are able to measure the volumetric flow of fluid, however, there are an increasing amount of areas where a measurement of the mass flow is desired. The mass flow is the amount of mass that passes through a tube in a certain amount of time. Coriolis flow meters are specifically designed to measure this mass flow rate.

The Coriolis Effect

Most people are familiar with the fact that water spins the opposite way when draining in the southern hemisphere than it does in the northern hemisphere. This is due to the rotation of the Earth itself. One way to envision this effect is to imagine a point mass moving in a straight line along the radius of a circle. If, however, the circle is rotating and the point mass is not connected to this circle, then the mass will take a curved path from the perspective of the circle. This is the Coriolis Effect.

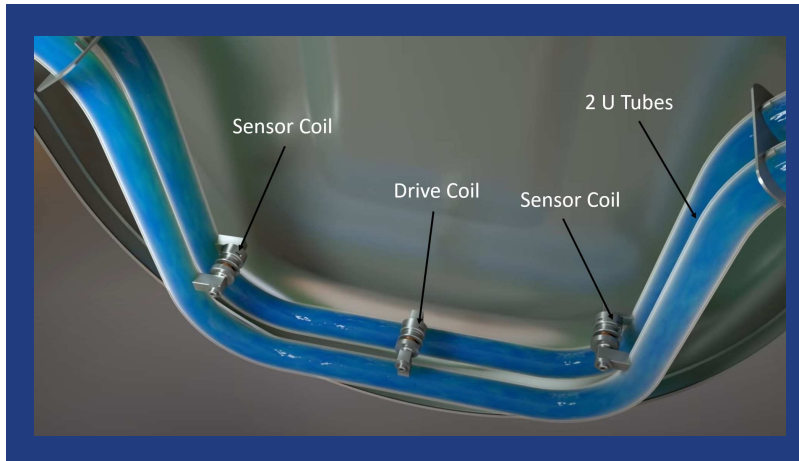
Knowing that this effect exists, a discerning engineer can pull out information about the moving object by the clever selection of reference frames.



Background

Coriolis Flow Meters

A Coriolis flow meter uses the Coriolis force and Newton's second law of motion ($F = m \cdot a$) to determine the mass flow of fluid through the meter. If both the force and acceleration of the fluid are known, then it is just simple algebra to solve for the mass. If this calculation is done over a specified time, then one can determine the mass flow.



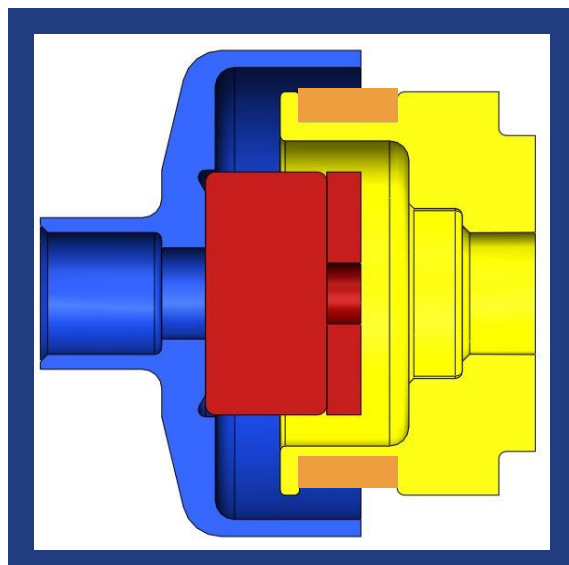
Coriolis Flow Meter - Internal

The mechanics of a Coriolis flow meter involve a few main components; 2 U-shaped flow tubes, 1 drive coil, and 2 sensor coils. As fluid flows into a flow meter, it is diverted down the 2 U-tubes. The tubes are then oscillated by the drive coil at their resonant frequency.

Due to the Coriolis effect, the tubes twist and oscillate out of phase between the inlet and outlet sensor coils. The magnitude of the phase offset is proportional to the mass flow of the fluid.

Voice Coils

In Emerson's Coriolis flow meters, both the sensor and drive coils all use the same design. The blue component in the image to the right is the **keeper**, a piece designed to direct magnetic flux in the most efficient direction. The red component is a permanent magnet. The yellow component is a ceramic **bobbin** that a wire (orange) is coiled around, creating an electromagnet. It is made of a ceramic to withstand high temperatures during operation (662 °F).

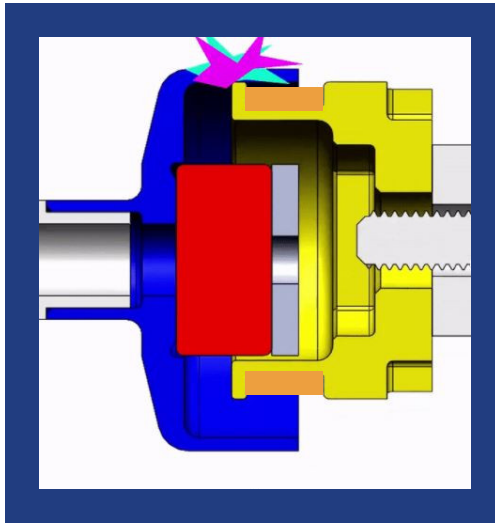


OEM Voice Coil

Increasing Robustness

Our Task

We were tasked to improve the reliability of Emerson's Coriolis flow meters by focusing our efforts on these voice coil assemblies.



OEM Device Collision

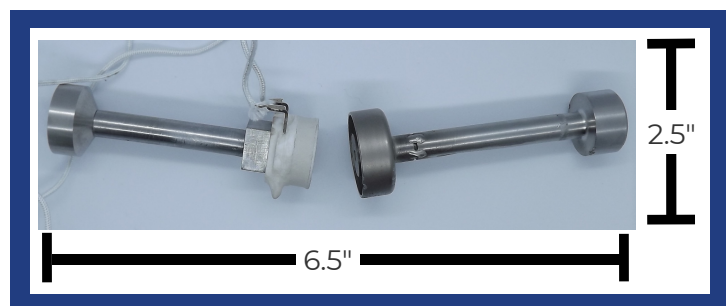
The main cause of failure are shock events caused by slug flow through the meter. These events are characterized by having a flow that consists of a long line of gas followed by a burst of liquid. This phase change exerts a shock load on the system. When the voice coil assembly is exposed to shock loading, the two halves of the assembly move relative to each other, and the brittle ceramic bobbin, shown in yellow, cracks due to impacts with the other metal components. This impact can be seen on the left with the pink/blue spark.

This results in the voice coil assembly and the whole flow meter being scrapped as it is hermetically sealed and can therefore, not be repaired after the fact.

Brainstorming

Initial ideation focused on increasing the robustness to withstand a 50 lbf load, without substantially decreasing electromagnetic efficiency. Efficiency, in this context, is characterized by the Lorentz force between the magnet and coil.

In order to obtain accurate measurements, the voice coil must be able to output a force of 0.0031 lbf. Additionally, designs needed to be no more than 6x1.7x1.7" in size in order to integrate with the flow tubes.

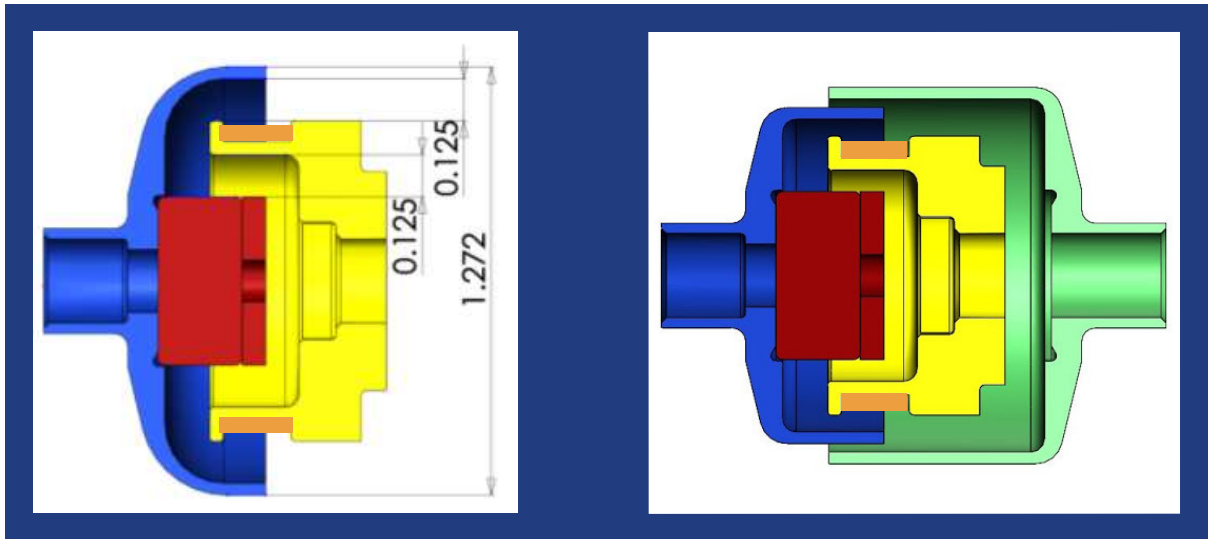


OEM Device Size

Design Process

Initial Design Ideas

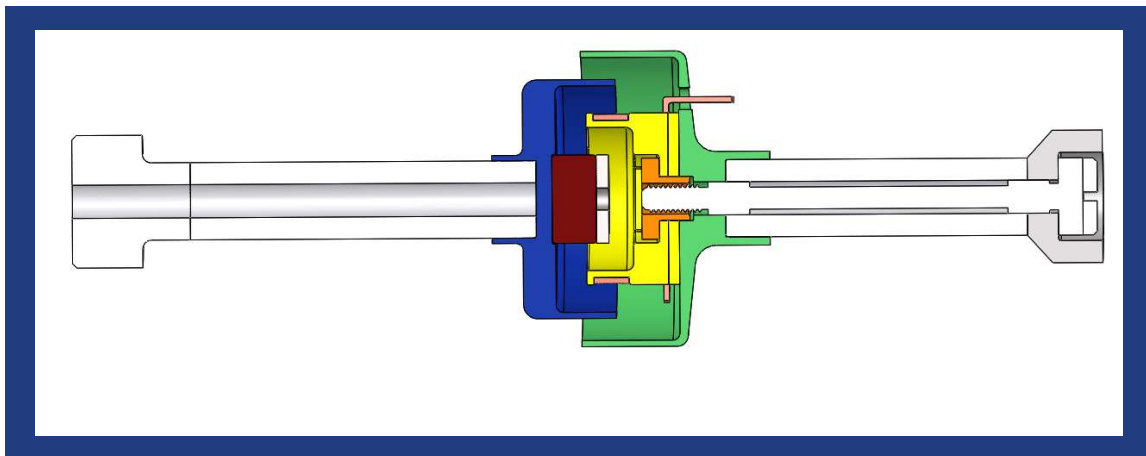
Based on the initial design requirements, we arrived at two designs that showed great potential. The expanded design aimed to increase all the critical radial dimensions. This would allow more movement in the directions of concern and decrease the failure rate. The constraint design was aimed at physically constraining the two halves in the directions of concern while allowing movement in the sensing direction. This added a hard stop that would prevent any collision with the brittle bobbin.



Expanded

Constraint

In the end, we combined both of these ideas to create our final design shown below. This decision was based on feedback from our client, our director Robert Linden, as well as a preliminary analysis of the electromagnetic efficiency of each design.

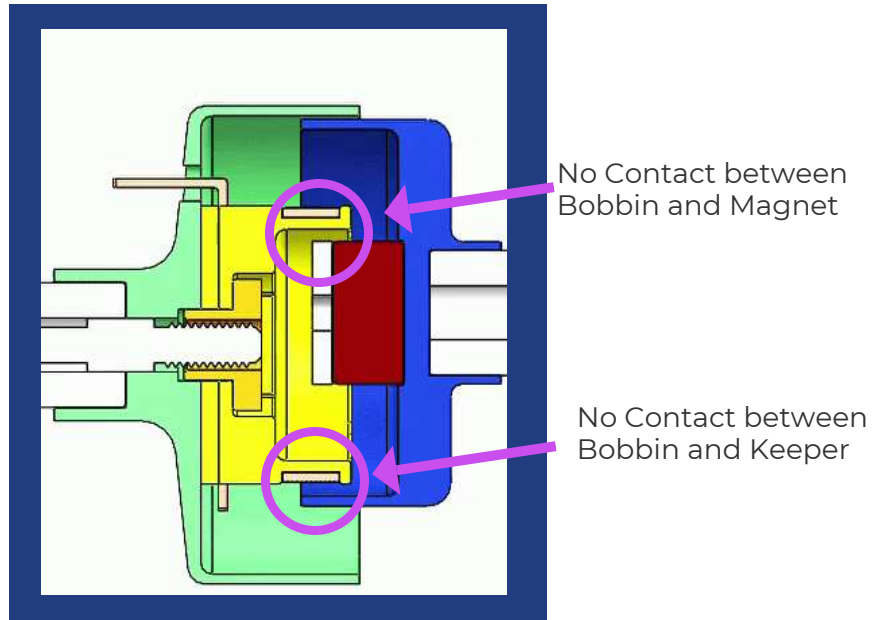


Team 22 Final Design

Final Design & Prototyping

Our design both increased the radial spacing between the components in the original assembly and added a constraint component, the sleeve.

The increased spacing allows the flow meter to have a larger operating range as it will impact less often. The sleeve, shown in green, ensures that on the occasion that there is an impact, it occurs between metal components instead of a brittle ceramic which cracks more easily. The images below showcase the bobbin not contacting at the two extreme positions.



Bobbin Clearance

Prototyping

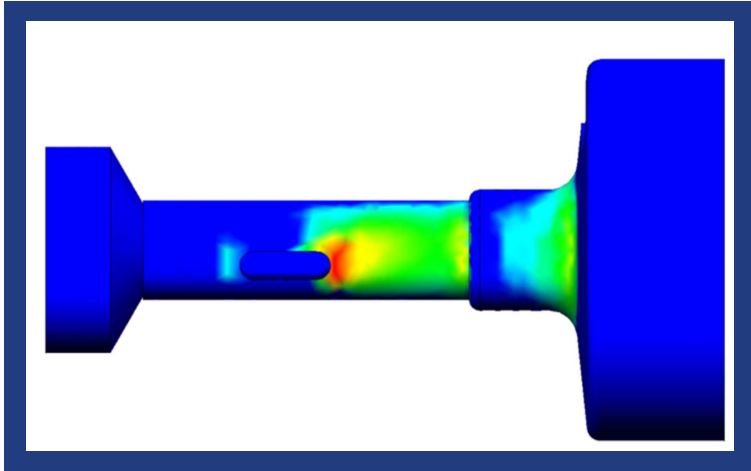


3D Printed Prototype

We prototyped our design by using 3D printed parts and PVC tubing. The aim was to ensure that the sleeve impacts the keeper as expected, the interface with the flow meter is held constant and that our stress flow is consistent with our intuition. Fortunately, the prototype shed light on design changes that reduced the complexity and showed that it functioned properly. Unfortunately, it failed at a location we were not expecting. However, this was attributed to us not using the final materials and the joints being glued together.

Analysis & Manufacturing

Structural Analysis



Solidworks FEA Stress Plot

Based on these results, we implemented changes to the design that were mostly focused on increasing the size of the fixture rods to raise our factor of safety from 1.3 to 2.

Electromagnetic Analysis

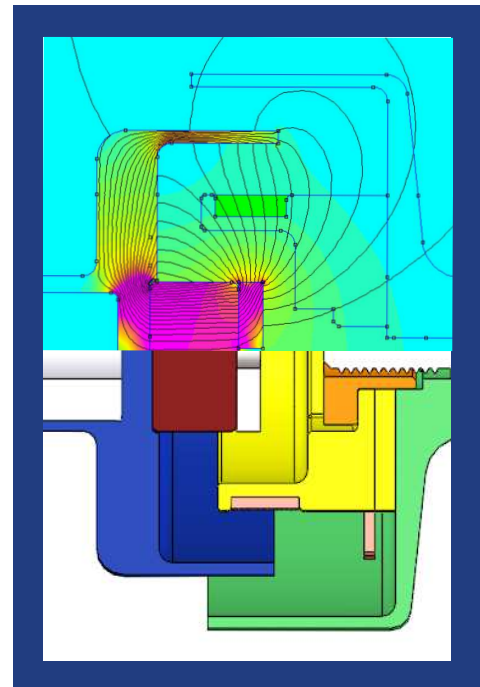
The electromagnetic efficiency analysis was conducted with FEMM. The magnetic flux plot can be seen to the right.. It was found that the main cause of our design having decreased efficiency is due to the increased radial size. This allowed us to compare our design to the original design and the design requirement, to set limits on the size of our design. Our design is 25% more efficient than the design requirement and 34% less efficient than the original design.

Manufacturing

Based on the findings from the analyses and prototyping, we proceeded with the manufacturing of our design. We constructed all the drawing packages and sourced the raw materials.

Emerson manufactured all of our voice coils through machining most of the components on a lathe and brazing or welding the parts together.

Following the selection of our final design, we spent two months thoroughly analyzing it. This allowed us to prove that the design met all the requirements. The first major analysis consisted of structural FEA of the assemblies. This was conducted through hand calculations and Solidworks' static FEA tool. The picture shows the stress flow in one half of the voice coil to 50 lbf.



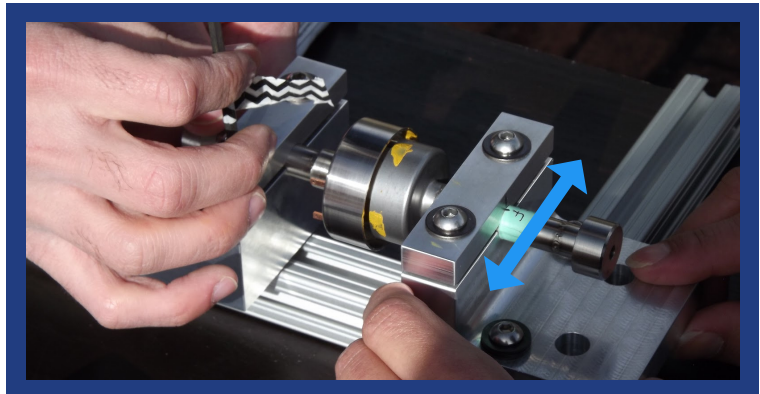
Magnetic Flux Plot

Design Validation

We conducted two testing phases to validate our design requirements. The first phase of testing involved developing test procedures, designing test fixtures, and commission testing. The second phase of testing allowed us to refine our procedures and fixtures to obtain more accurate results, as well as introduce the static load to failure, and shock study discussed on the next page.

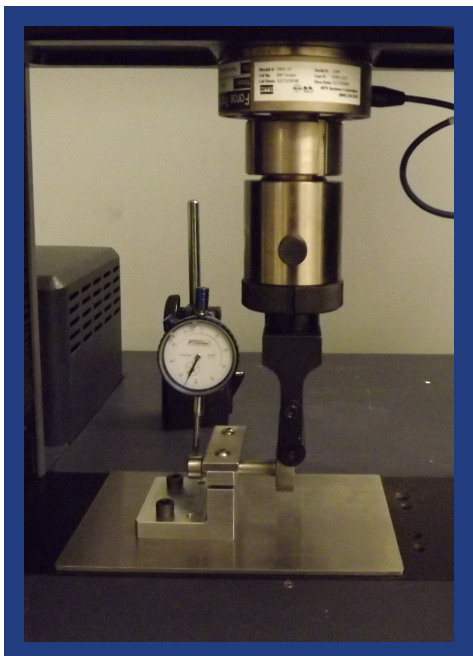
Mechanical Interference Test

In our first test, we checked whether our sleeve functioned properly by determining whether the first and only point of radial contact was between the keeper and sleeve. We tested this with yellow gear marking compound. Through visual inspection, we were able to see that our design prevented contact with the brittle ceramic bobbin.



Mechanical Interference Test

Static Deflection Test



Static Deflection Test

The next step was to determine whether our design could withstand a load of 50lbf, the expected force experienced in failure events. This was performed with a Universal Testing Machine which applied the static load at the end of each half of the assembly.

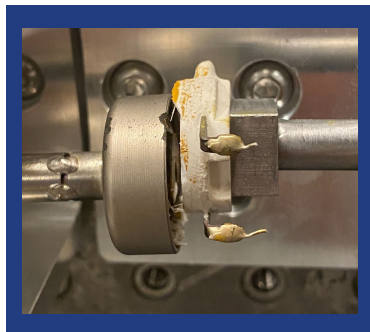
During the test, we did not see any permanent deformation through visual inspection. When we plotted the force vs displacement, we confirmed the lack of plastic deformation, due to the curve being linear (i.e. we were in the elastic regime). Therefore, we were able to confirm that our design is statically robust to the loads experienced during the failure event.

Design Validation

Static Load to Failure Test

As with any design, it is important to understand the design limits. This test had the same setup as our static deflection test but we increased the load until failure, defined for the purposes of our project as plastic deformation. This occurred at 125lbf, which showed that our design has a factor of safety of 2.5, and that the brittle bobbin fails after other components. As a result, our design has increased the robustness to static failure and is able to withstand equivalent static loadings that are over double the load that is expected during the failure event.

Shock Study



OEM Device after 417 G's

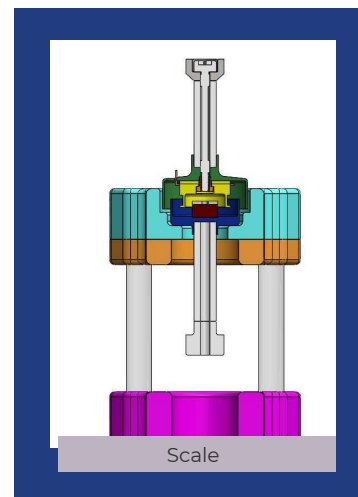


Team 22 Device after 570 G's

The previous tests have shown that our design is robust to static loading events, however, the failure event arises from dynamic forces. The shock study explored the robustness of our design compared to the original assembly. Specifically, both assemblies were exposed to increasing shock loads using a drop shock tower. The original design experienced brittle failure at a force of 417 G's, while our new design showed no failure even after repeated exposure to the maximum shock loading of 570 G's. This shows that our new design is sufficiently more robust to shock than the original.

Magnetic Pull Test

The final design specification that had to be validated was the electromagnetic efficiency. This was accomplished by passing the specified current of 10 mA through the coil and measuring the force output with a scale. This force is equal to the Lorentz force of the assembly. The resulting efficiency was below the original design because we had increased the size, however, we were able to achieve a force of 0.00389 lbf, which is well above the required force of 0.0031 lbf.



Magnetic Pull Test Setup

Conclusion & Next Steps

Design Implementation

While future testing needs to be done on our design, we have produced an economically viable solution to the robustness problem while maintaining the function of the voice coils. Since our design is so heavily based on the OEM voice coil, there should be little difficulty implementing our design into Emerson flow meters for production.

Future Work

The end goal would be to mount our design onto the existing flow meters. However, as with most commercial products, they have to go through extensive testing processes. This will most likely consist of the following groups:

- **Device Testing** - Vibration testing, Environmental and lifecycle testing
- **Performance Testing** - Mass flow measurements when mounted to flow tubes
- **Further Problem Evaluation** - Identification of the forces in slug flow events

Closing Remarks

This project had a broad design space as the failure magnitude was effectively unknown due to the complexity and variability of failures. Our team worked effectively over this 9 month period to explore numerous design avenues, analyze and prototype the final design and thoroughly test the recommended assembly. The outcome showed that our design has a sufficient factor of safety to both dynamic and shock loading, has the necessary electromagnetic efficiency to function as a voice coil assembly and mitigates the old failure point by moving the collision location. Therefore, our design met the original goals of increasing the robustness of the system, in a general sense, to account for any uncertainties in the specifications while preserving sufficient electromagnetic efficiency.

Meet the Team - Team 22



James Brown

Logistics Manager

James was able to contribute to many aspects of engineering, while being the main point of contact between the team and outside resources. He came up with and designed the Sleeve component, performed structural analysis, by hand and through FEA, and lead magnetic pull testing.



Gretchen Conley

Head of Testing & Systems

Gretchen developed project requirements, test procedures, and lead data analysis. She adapted to changes in the project as necessary to ensure completeness of testing.



Axel Escareno

Head of Manufacturing

Axel made certain that our design was manufacturable by providing industry standard drawings to the machinists that worked on the parts, along with quality checking the parts once they were manufactured to ensure specification requirements.



Reed Harrington

Financial Manager

Reed was integral to keeping the project on track by managing the budget and ordering supplies. He also assisted with design work during the first semester and focused on the static failure testing during the second semester



Justin Lim

Head of CAD and Design

Justin spearheaded learning the Finite Element Method Magnetics program that solves for our device's electromagnetic efficiency. He worked heavily in SolidWorks for our device and fixtures, as well as organizing our files and iterations



Tristan Schoeman

Project Manager

Tristan laid out the entire project and adjusted the schedule based on developments throughout the project. He checked in with team members and distributed work to ensure that the project could run smoothly. In the first semester, he performed structural analysis of the design and in the second semester he pivoted to focusing on the shock testing.