Characterization of eddy-current repulsion of conductive, non-ferromagnetic foams

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Eddy-current repulsion has been extensively studied in non-ferromagnetic, solid plates, however, to the author's knowledge, this has not been quantitatively examined in non-ferromagnetic, porous structures. These structures are lower in density than their solid counterparts yet maintain high structural integrity, which may provide savings in launch mass for space applications. This work experimentally characterizes the eddy-current repulsion of aluminum foams and demonstrates sufficient repulsion (>10 mN) for manipulation in microgravity environments over a range of separations. This work also contributes to an experimental testbed for force measurement. These results may provide a future for non-ferromagnetic, conductive foams as materials allowing for eddy-current manipulation in space.

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I. Introduction

Non-ferromagnetic, solid aluminum is a commonly used material in the aerospace industry for structural and heat shielding purposes. Metal foams have emerging applications in these areas due to their low mass density, high mechanical strength and high thermal conductivity, among other properties [1]. This low mass density enables lower payload mass and lower launch costs for spacecraft. According to Lenz's law and Faraday's law of induction, eddy currents are generated in conductive materials and provide a force opposing a change in magnetic flux [2]. Non-ferromagnetic, conductive materials such as aluminum ensure that there is no net attraction between the material and the magnet at rest.

Eddy-current actuation is a proposed technology for non-contact manipulation in space such as damping during docking [3], changing attitude [4], and regular repairs and servicing of spacecraft [5]. Since non-contact techniques are crucial in minimizing wear and tear, this can allow us to design missions with longer lifetimes. Previous research [6] has shown eddy-current sensing in foams using a modified conductivity model but has not quantitatively measured repulsion on foams. This research demonstrates eddy-current repulsion force on aluminum foams.

II. Materials and methods

A. Material selection

To quantify the effects of repulsion force on non-ferromagnetic samples, this work compares a solid plate with a compressed open-cell foam. Open-cell foams (Figure 1) consist of interconnected pores or membranes with no layer of material separating the pores. A compressed foam sample increases the relative density, which allows direct comparison between the amount of material to a solid plate of a similar alloy and dimensions. Table 1 lists the samples used for the experiments as well as their properties.

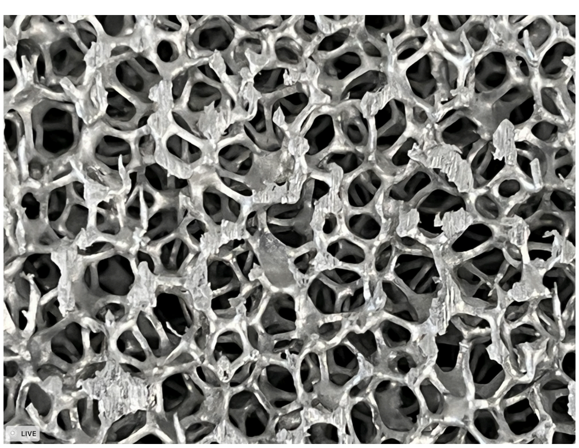

Figure 1: Open-cell foam structure of sample with properties in Table 1

Table 1: Sample properties

Sample type	Dimensions	Alloy	Relative density[1]	Mass (g)
Solid aluminum plate	6 inches by 6 inches by 0.08 inches	6061-T6[2]	100%	131.2
Compressed aluminum foam	6 inches by 6 inches by 0.5 inches	6101-T6[3]	18-20% after compression from original 1 inch height	160.1

$$RD = \frac{weight}{volume * \rho_{base}} * 100\%$$

B. Finite Element Analysis Models

COMSOL finite element software modeled the eddy-current repulsion force for the solid aluminum plate with size and conductivity in Table 1 [7]. The dimensions of the coil used are as follows: an outer diameter of 2.7 inches, inner diameter of 1.9 inches, and 500 turns. Figure 2 shows the geometry of the coil and solid plate. Table 2 summarizes the number of degrees of freedom used for each relevant separation. The model has a current amplitude of 1.0 A which is then scaled to the average current amplitude measured among all experimental trials. This relationship can be used since the repulsion force is proportional to the squared current amplitude [8].

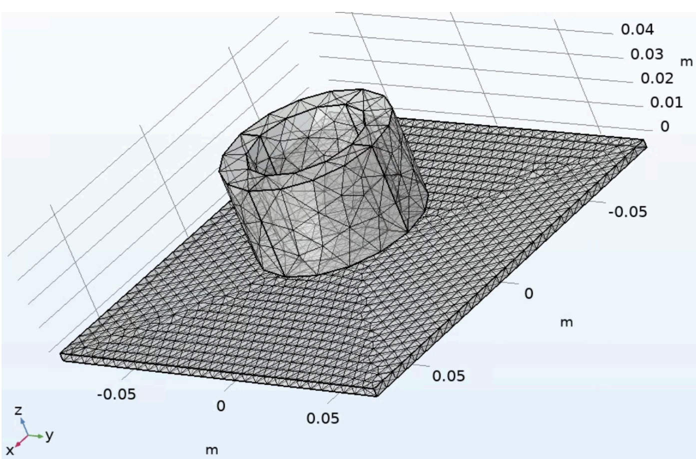

Figure 2: COMSOL model showing coil and solid plate geometry with mesh elements

[1] ERG Aerospace. Duocel Foam - Electrical Conductivity. https://ergaerospace.com/duocel-foam-electrical-conductivity/.
[2] ASM Aerospace Specification Metals Inc. Aluminum 6061-T6; 6061-T651. https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma6061t6.
[3] MatWeb Material Property Data. Aluminum 6101-T6. https://www.matweb.com/search/DataSheet.aspx?MatGUID=4303c5b908ff4cbd91a02fed7d4e8202&ckck=1.

Table 2: Summary of model separation, repulsion force and number of degrees of freedom

Model separation (mm)	**Eddy-current Force Magnitude, z-component (mN)**	**Number of Degrees of Freedom**
0	68.1938136	1,524,352
1	59.4874508	1,525,236
2	52.1380009	1,524,990
3	45.8528202	1,521,942
4	40.4146927	1,524,222

C. Experimental setup

The experimental setup involves design and use of custom hardware attachments to suspend the samples from the force sensor (IMADA DST-1A). This setup includes a laser-cut force sensor bracket as well as 3D-printed (PLA plastic) sample holder top/bottom plates and spacers (Figure 2). To generate eddy currents, the experimental setup uses an AC coil in a 1.085 kHz resonant circuit (Figure 3) to provide a current amplitude of 1.000 A with a standard deviation of 0.215 A across all trials. This value is measured from the current output of the Accel Instruments TS250-1 amplifier using a Tektronix TDS210 oscilloscope. The resonant circuit consists of a coil (1.9 inch inner diameter, 2.7 inch outer diameter, 1.5 inch height, 500 turns, 4 Ohm resistance, and 11.95 mH inductance), an Accel Instruments TS250-1 amplifier, a Siglent SDG1025 function generator, and a 1.8 μF capacitor connected in series.

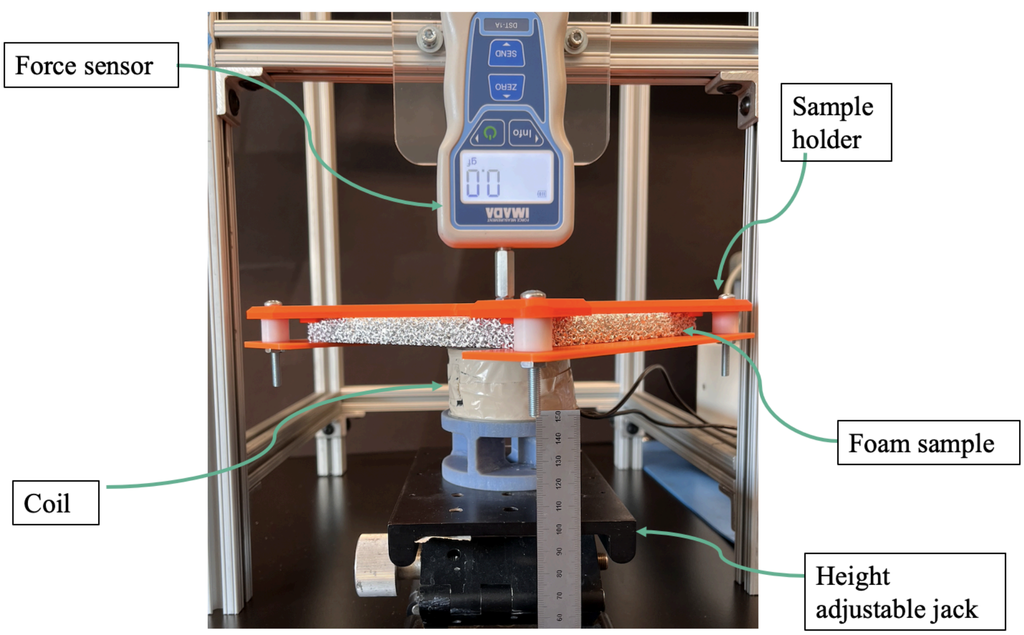

Figure 2: Labeled experimental setup for suspended force sensor

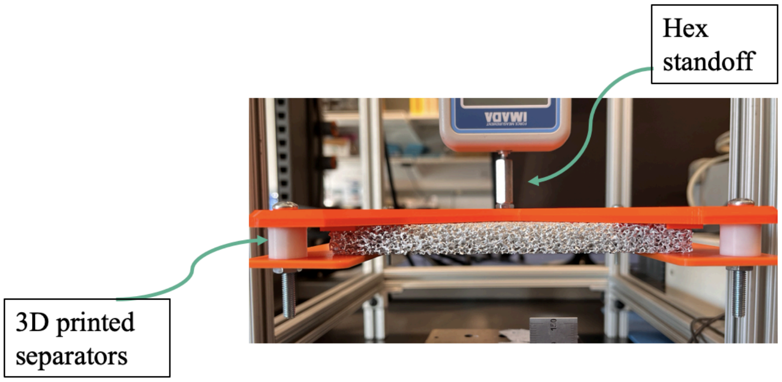

Figure 3: Close-up of sample with labeled custom hardware attachments

The jack in Figure 2 is used to adjust separation between the coil and the sample to a 0.5 mm precision using the attached ruler. The point of "0 mm separation" is defined as the point where the coil just contacts the sample, where the force sensor still reads a value of zero.

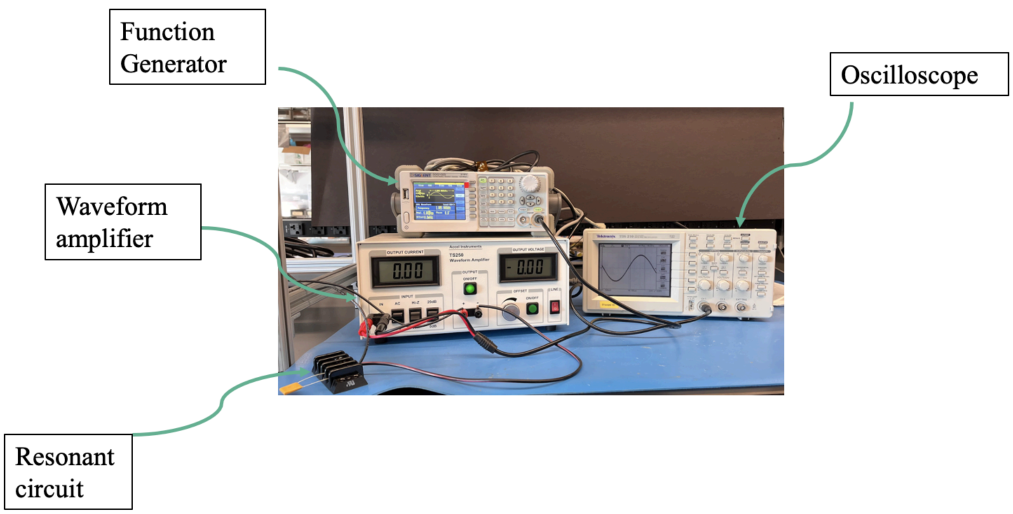

Figure 4: Experimental setup for resonant circuit as shown in Figure 5

D. Repulsion force vs frequency measurements

This study compares the FEA modeled results with experimental data collection of repulsion force. For each sample, five trials are conducted at each separation (0.0 mm, 1.0 mm, 2.0 mm, 3.0 mm). Since the force sensor records mass in grams, the study takes a starting mass measurement with the coil off and subtracts subsequent mass measurements with the coil in operation to obtain the repulsion force.

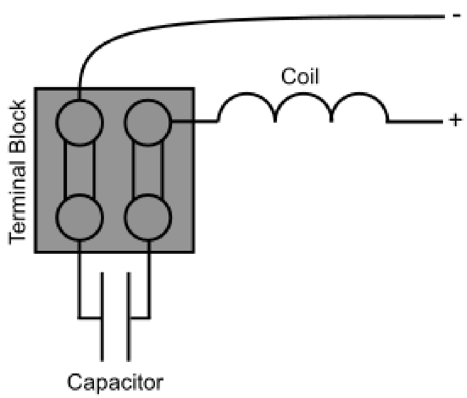

Figure 5: Resonant circuit[4] schematic for AC coil operation with end leads connected to the waveform amplifier

III. Results and Discussion

The following figures highlight the results for the modeled and experimental force versus separation sweeps. The modeled repulsion force in Figure 6 shows an exponentially decaying behavior as the separation increases. The FEA model consists of a separation sweep, hence the continuous line. Relevant separation values that correspond to the experimental separations are plotted as points.

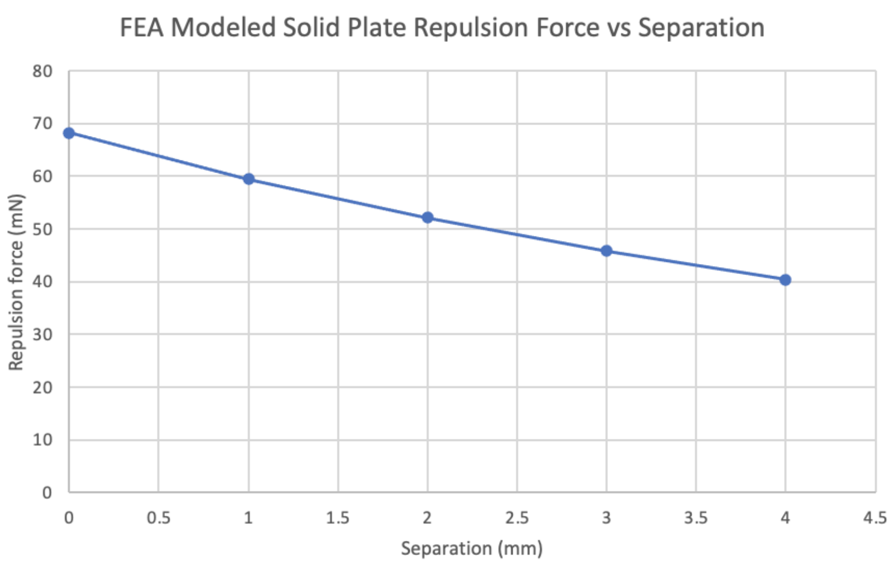

Figure 6: FEA modeled electromagnetic repulsion force as a function of separation in mm

[4] Accel Instruments. High-Frequency Electromagnet Using Resonant Technique. https://www.accelinstruments.com/Applications/WaveformAmp/Electromagnetic-Coil-Resonant.html.

The experimental repulsion force results in Figure 7 show a similar decaying behavior between repulsion force and separation. The force sensor has an accuracy of ± 1.0 g which means that a registered force of 19.8 mN indicates that a repulsion force of at least 10 mN has been provided. Comparing the experimental and modeled results for the solid plate show that the experimental repulsion is higher in magnitude than the modeled repulsion force by a factor of 1.3 for the repulsion force at zero separation. The compressed foam has a lower overall repulsion force magnitude than the solid plate by a factor of 1.8 which makes sense due to the lower relative density and lower electrical conductivity. However, the repulsion force is still comparable to that of the solid plate. This shows that the relative density does lower the repulsion force magnitude but it is not linearly related. Other sources of error may include AC current-induced vibrations at the point of contact between the coil surface and the sample and overheating of the resonant circuit elements causing unstable current amplitude supplied to the coil.

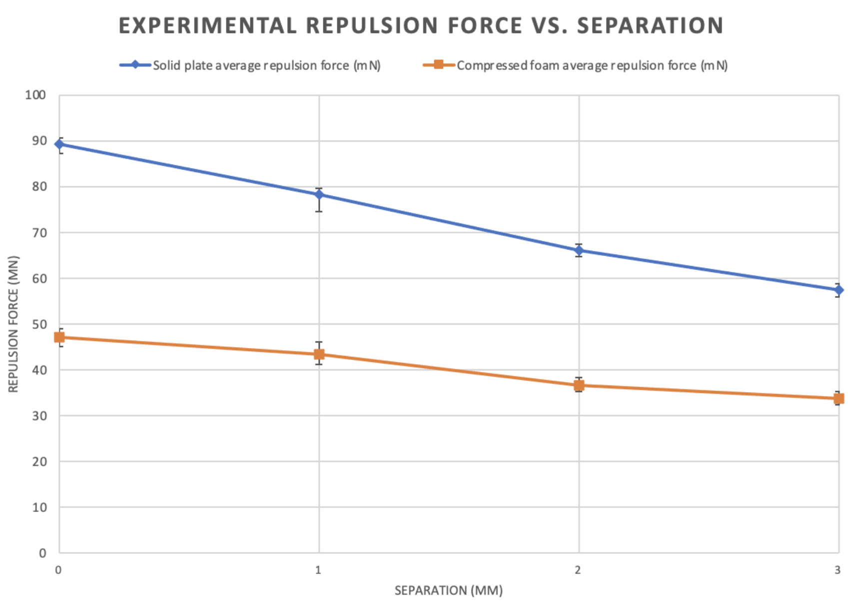

Figure 7: Experimentally measured repulsion force as a function of separation in mm

IV. Conclusion

This work contributes a testbed setup for experimentally taking repulsion measurements and demonstration of greater than 10 mN repulsion on an aluminum foam. Both the experiment and model results support that at least a 10 mN repulsion force can be observed on foams. However, the solid plate model deviates from experimental results by 30%. This difference may be reduced in future work by refining the FEA models for better fit and readjusting how variation in separation is measured. Additional refinement steps may involve using a scaled conductivity model for the foam in an FEA model and using samples with different relative densities to attempt to further quantify the relationship between relative density and repulsion force magnitude. Future work may also include investigating non-ferromagnetic perforated plates as other low-density alternatives that may extend potential opportunities to reduce launch mass in space.

Acknowledgments

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[7] COMSOL, AC/DC module, Software Package, Ver. 5.6

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