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The Influence of Coil Winding Gap and Armature Material on the Performance of Magnetic Flux Compression (MFC) Squeeze 5 Device

by George B Vunni

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Weapons and Materials Research Directorate, CCDC Army Research Laboratory

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14. ABSTRACT The effect of coil (stator) winding gap (the space between the coil turn) and armature material on magnetic flux compression devices has been analyzed using the ALE3D magnetohydrodynamic code. Three winding gaps are considered: 12.70, 6.35, and 3.18 mm. For an aluminum armature (a hollow seamless metal tube filled with high explosive), the 6.35-mm winding gap performed better than 12.70- and 3.18-mm gaps. For copper armature, the 6.35- and 12.7-mm winding gaps produced the same compressed current output that was higher than the 3.18-mm gap.						
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1. Introduction

Magnetic flux compression (MFC) generators are attractive energy sources for compact pulsed-power systems. The MFC design in this work consists of a conducting cylindrical coil (stator) and a coaxial, conducting cylindrical tube (armature) filled with high explosives. The coil is energized by a seed current, with a return path via the load and armature. When the explosive is initiated, the armature rapidly expands, trapping the magnetic flux in the shrinking volume between the coil and armature. As the detonation moves forward, the coil is shorted out turn by turn by the armature, resulting in the reduction of the circuit inductance and increase in the current.

In previous works, ALE3D magnetohydrodynamic (MHD) simulations of internal inductance and current using the Squeeze 5 MFC device was reported.¹⁻³ The objectives of previous reports were to establish a set of simulation techniques and parameters in ALE3D that produced similar experimental measurements of the device inductance, and the compressed current. In this report, three-dimensional (3-D) ALE3D-MHD simulations were performed to investigate the effects of the coil winding gaps and armature material on the performance of the Squeeze 5 MFC device that was designed at the US Army Combat Capabilities Development Command Army Research Laboratory. The primary goal was to determine the optimum coil winding gap that resulted in the best performance of the MFC. Three winding gaps were considered. Figure 1 shows the images of the three coil winding designs with gaps of 12.70 mm (1/2 inch), 6.35 mm (1/4 inch), and 3.18 mm (1/8 inch). In these designs, the number of turns was kept constant.

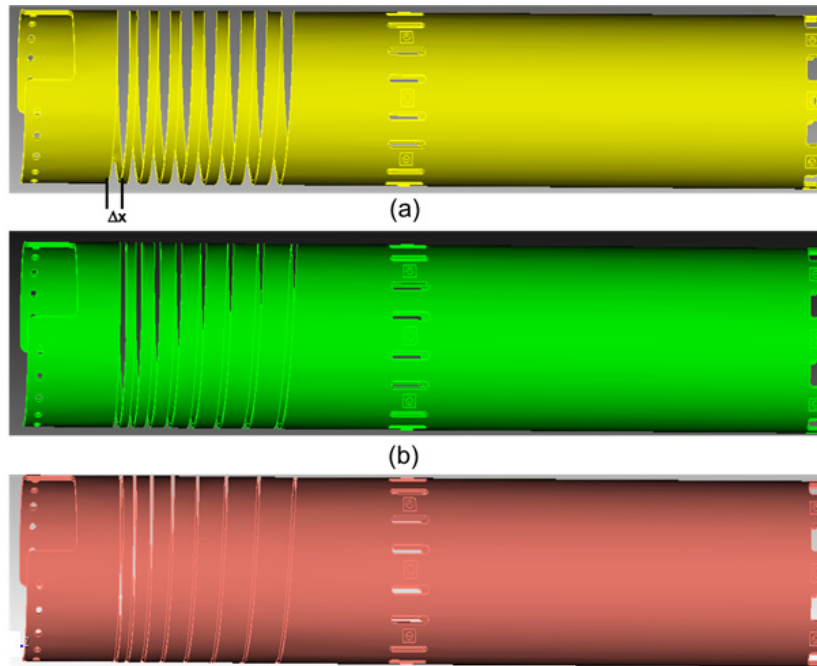


Fig. 1 Stator (coil) design showing variation of the coil winding gaps. a) $\Delta x = 12.7\text{-mm}$ (1/2-inch) gap, b) $\Delta x = 6.35\text{-mm}$ (1/4-inch) gap, and c) $\Delta x = 3.18\text{-mm}$ (1/8-inch) gap.

2. Brief Description of the Squeeze 5 MFC Device

Details of the Squeeze 5 MFC generator design can be found in Vunni et al.¹ and Vunni². In brief, it is composed of C12200 copper coil (stator) with a 6063-TO aluminum armature. Figure 2 shows a schematic drawing of the device. The armature tube has a 71.6-mm outer diameter and 4-mm wall thickness. A phenolic resin tube with 3-mm wall thickness was filled with Composition B explosive and inserted into the armature the day of the flux compression experiment. The variable coil pitch was machined from a 130-mm outer diameter aluminum tube. A 6.4-mm slot was cut into the tube, using a 4-axis mill, to create a 7-turn coil. The coil's conductor width is smallest at the initiation end of the device and grows in width to its maximum at the generator end. This increasing cross-sectional area of the conductor prevents coil melting or vaporization as the current builds in the device during its function.

3. ALE3D-MHD Code

ALE3D's MHD model is capable of capturing the dynamics of electrically conducting solids and fluids. The MHD module was developed primarily for the modeling of coupled electro-thermal-mechanical systems that are inherently 3-D in nature. Example applications for this capability include explosively driven MFC generators, induction heating, metal forming, and electromagnetic rail gun systems.

The ALE3D-MHD module solves the resistive magnetic induction equation given a collection of specified current and voltage sources. The equation is solved in the Lagrangian frame using a mixed finite element method employing H (Curl) and H (Div) finite element basis functions that preserves the solenoidal nature of the magnetic field to machine precision. Electromagnetic force and resistive Joule heating terms are coupled to the equations of motion and thermal diffusion in an operator split manner. For problems that require mesh relaxation, magnetic advection is performed using the method of algebraic constrained transport that is valid for unstructured hexahedral grids with arbitrary mesh velocities. The advection method maintains the divergence-free nature of the magnetic field and is second-order accurate in regions where the solution is sufficiently smooth. For regions in which the magnetic field is discontinuous (e.g., MHD shocks), the advection step is limited using the method of algebraic flux correction as explained in detail the ALE3D manual.⁴

4. ALE3D-MHD Simulation

ALE3D simulations were conducted to determine the effect of the coil winding gaps and armature material on the performance of the MFC device. Previous work reported the simulation setup and methods.^{1,2} Similar techniques were followed in the present work. In the first series of simulations, three ALE3D-MHD simulations were conducted to investigate the performance of the flux compression generator with aluminum armatures and coil winding gaps (the coil material was copper) of 12.70, 6.35, and 3.18 mm. In the second series, the aluminum armature was replaced with copper material while keeping everything else the same. The computational setup, material models, external seed current, and mesh configurations were kept as reported in Vunni et al.¹ and Vunni².

5. Simulation Results

5.1. Aluminum Armature: Copper Coil

Figure 3 shows the current profiles and time derivative (dI/dt) from the ALE3D-MHD simulations for the three coil winding gaps shown in Fig. 2 using a 110-kA seed current. The experimental current for a winding gap of 12.70 mm is plotted for comparison. The peak amplified currents for the three winding gaps are 0.933, 0.970, and 0.955 MA, which represents current gains of 8.5, 8.8, and 8.7, respectively. The simulation predicted the highest current amplification for a coil winding gap of 6.35 mm with a current gain of 8.8, followed by winding gaps of 12.70 and 3.18 mm. For a winding gap of 12.70 mm, the simulation underpredicted the current by 25 kA, approximately 3% less than the measured peak current of 0.980 MA (980 kA).

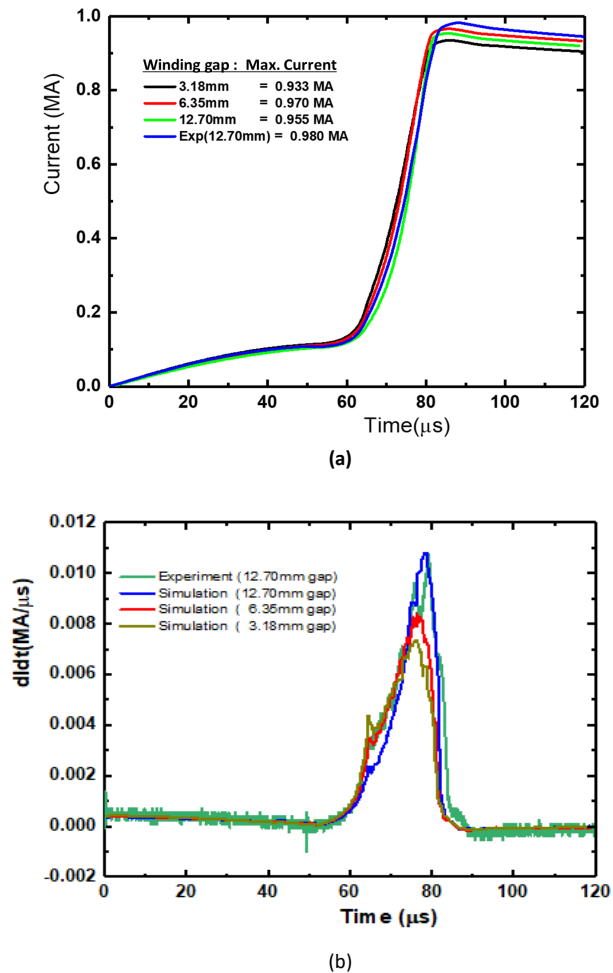


Fig. 3 Comparison of ALE3D-MHD results: a) current and b) dI/dt for coil winding gaps of 12.70, 6.35, and 3.18 mm with aluminum armature

Figure 4 shows the time-varying inductance for the three coil winding gaps. The initial inductance before compression ($t < 60 \mu\text{s}$) increases with the winding gap size. At later times (end of compression), the inductances all converged. The observed difference of the initial inductance may be due to the variation of coil area. For coil inductance calculations in general,⁵ greater coil area results in greater inductance; less coil area results in less inductance. Greater coil area presents less opposition to the formation of magnetic field flux for a given amount of field force, since the inductance is derived from the magnetic energy extracted from the time-varying history of the scalar circuit current.^{1,2}

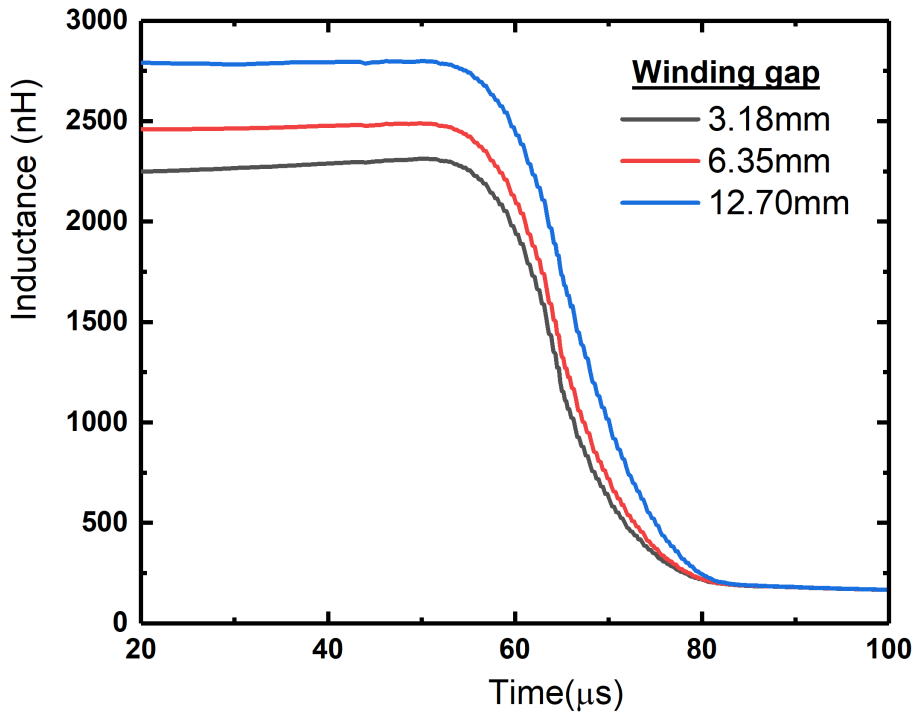


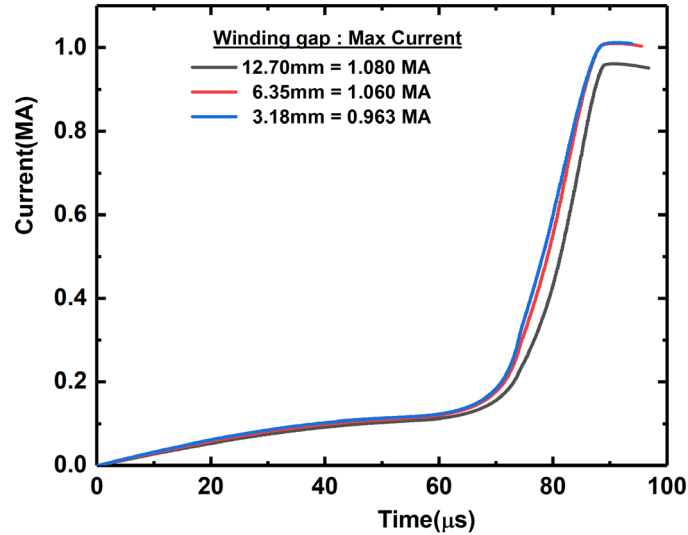
Fig. 4 Generator inductance (aluminum armature) for coil winding gaps of 12.70, 6.35, and 3.18 mm

We have shown previously that the effective inductance from ALE3D simulations is in very good agreement with the measured values for a coil winding gap of 12.70 mm.¹ Approximately 10%–15% difference was observed due to frequency dependence in the measurement and simulation. The experimental measurements were taken at a fixed frequency of 5 kHz, but the frequency varied in simulation as the inductance was reduced.

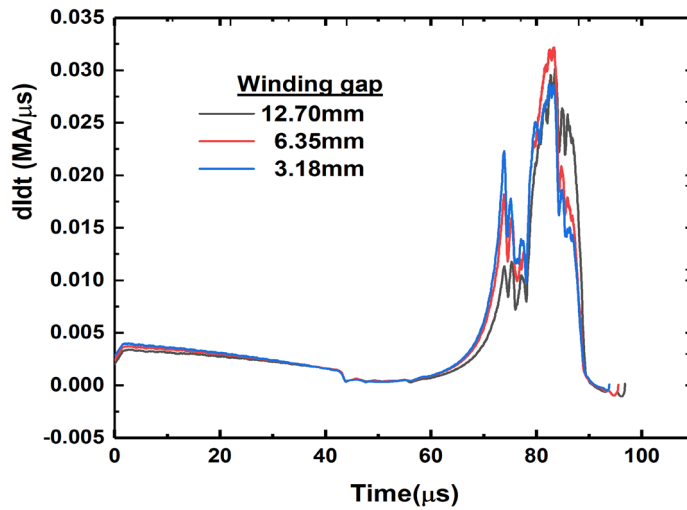
5.2 Copper Armature: Copper Coil

Figure 5 shows the current and dI/dt profiles from the ALE3D-MHD simulations for copper coil winding gaps of 12.70, 6.35, and 3.18 mm, with peak currents of

1.080, 1.060, and 0.963 MA, respectively. Similar peak current was obtained from the 12.70- and 6.35-mm. Like in the aluminum armature, the 3.18-mm coil winding gap produced a lower peak current.



(a)



(b)

Fig. 5 Comparison of ALE3D-MHD results: a) current and b) dI/dt for coil winding gaps of 12.70, 6.35, and 3.18 mm for copper armature

The current derivatives presented in Figs. 3b and 5b show a periodic spike when the armature/coil contact point moves to the next loop in the coil winding. The drop in dI/dt indicates electrical breakdown in the generator.^{6,7} The dI/dt for aluminum armature shows a small electrical breakdown (less periodic spikes observed in the

dI/dt plot in Fig. 3b), while the copper armature (Fig. 5b) shows a significant breakdown as shown in Fig. 6.^{6,7}

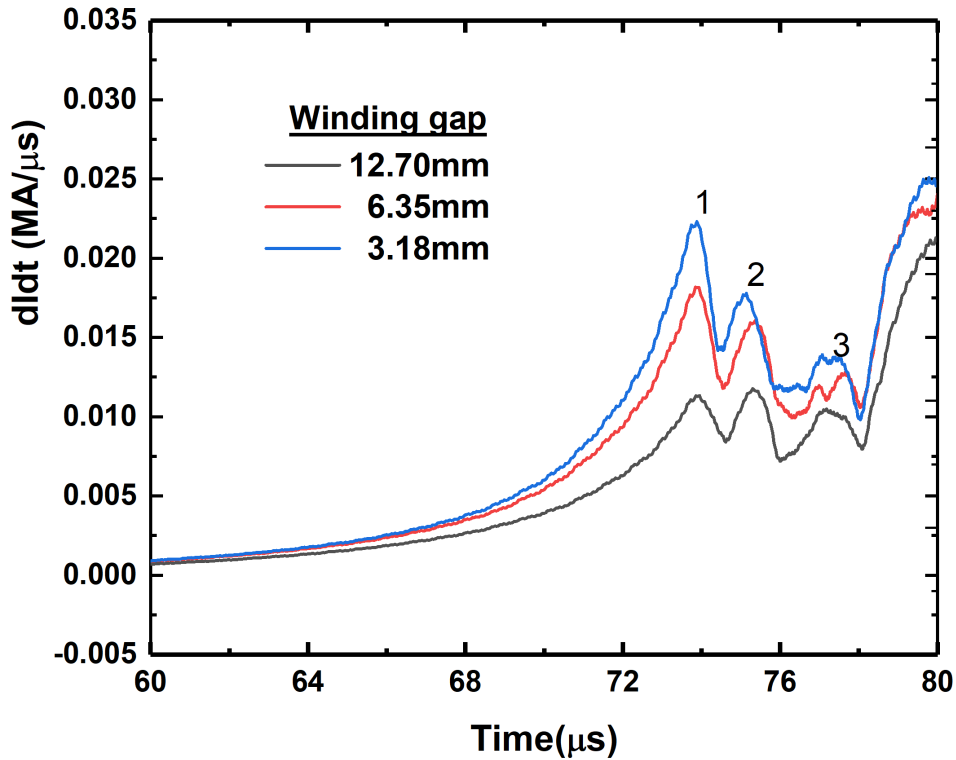


Fig. 6 Zoom box of Fig. 5b. Numbers indicate time at which (according to simulations) the armature makes contact with the first three turns: 1 = first turn, 2 = second turn, and 3 = third turn.

Figure 7 shows a snapshot of the expanding angle (for coil gap of 6.35 mm) at the following times after initiation of the high explosive: 67 μs for the aluminum armature and 75 μs for the copper armature. The expansion angle is defined as the angle of the line between the two points A and B relative to the generator axis. The expansion angle from the ALE3D simulation was found to be 13.0° for the aluminum armature and 9.0° for copper armature.

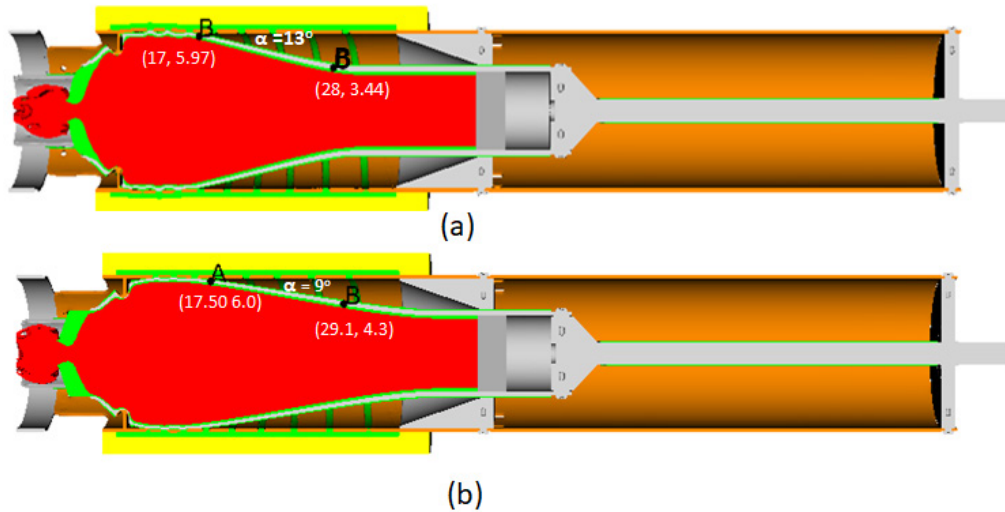


Fig. 7 Cone expansion snapshot with coordinates used to calculate the armature expansion angle: a) aluminum and b) copper armature

Figure 8 compares the maximum current for the three coil winding gaps. The copper armature produced higher maximum current than aluminum for all winding gaps. For both armature materials, the 3.18-mm winding gap produced low compressed current, while the 12.70- and 6.35-mm gaps have similar maximum current, which suggests that the performance of the device does not change much as the winding gap is equal or greater than 6.35 mm. Some of the observed dissimilarities in behavior of copper and aluminum armature can be explained by the difference in the electrical and thermal conductivity. Copper, with higher electrical conductivity, should exhibit smaller losses; however, in aluminum the rise of resistance with dissipated power is smaller than in copper.⁶ An important characteristic of a well-designed flux compression generator is that the skin depth must be smaller than the thickness of the armature enclosing the magnetic flux to avoid excessive loss during compression.⁵

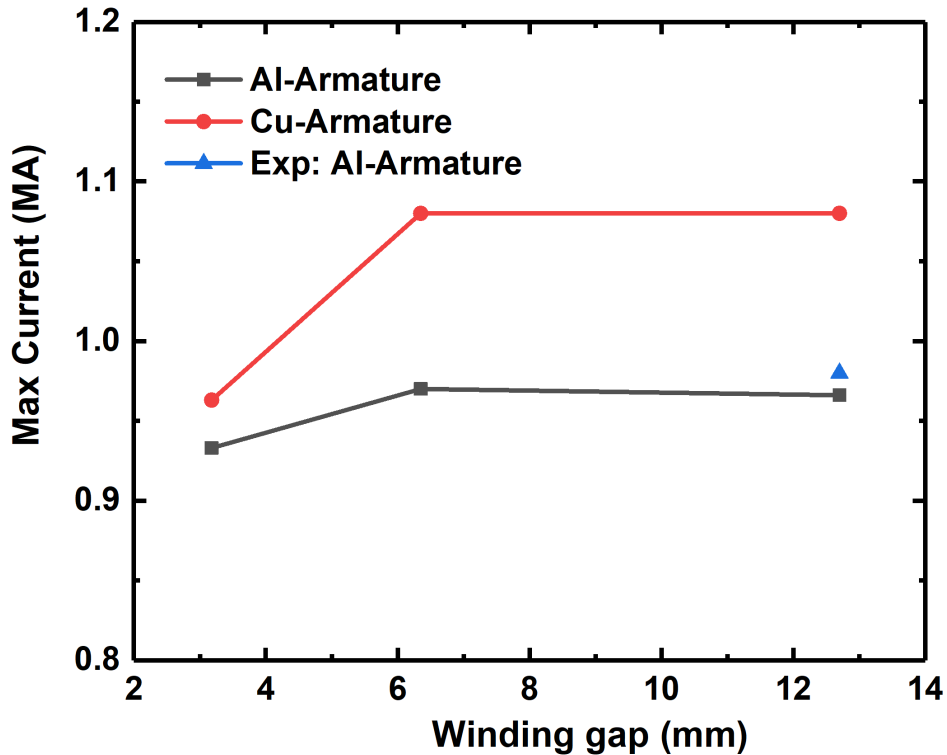


Fig. 8 Maximum peak current vs. coil winding gaps: aluminum armature (gray line), copper armature (red line), and experiment (blue triangle)

6. Conclusion

The performance of the Squeeze 5 MFC generator as a function of both coil winding gap and armature material was investigated using the ALE3D-MHD shock physics code. Three different winding gaps and two different armature materials were examined.

For aluminum armatures with winding gaps of 12.70, 6.35, and 3.18 mm, the compressed currents were 0.955, 0.970, and 0.933 MA, respectively. A winding gap of 6.35 mm gave the highest compressed current. For the winding gap of 12.70 mm, the measured maximum current from the experiment was 0.980 MA¹ compared to the simulated current of 0.955 MA. Reducing the winding gap from 12.70 to 6.35 mm increased peak output current by only 1.6%. Meanwhile, a coil winding gap of 3.18 mm produced a reduction of 2.3% in the peak current. The lack of sensitivity of the compressed current to winding gaps is interesting and needs to be studied in the future.

For copper armatures with winding gaps of 12.70, 6.35, and 3.18 mm, the simulated maximum currents were 1.080, 1.080, and 0.963 MA, respectively. The simulated

compressed currents with copper armatures are all higher than for the aluminum armatures.

For aluminum armatures, all the simulated peak currents are lower than the one experiment (for a winding gap results of 12.70 mm). We are still investigating the effect of advection and mesh resolution controls that may reveal if there is anything prematurely stopping compression of the flux.

Future plans include continuing to model and improve the MFC generator and changing from a static inductive load to a dynamic load. Additional experiments, using a copper armature, will help to understand the effects of armature material on the performance of the Squeeze 5 MFC device.

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