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3-D ALEGRA Simulations of Magnetic Field Shielding Effects of Conductive Tubes and Cups

by W Casey Uhlig

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14. ABSTRACT

Full 3-D ALEGRA simulations were used to understand the shielding effects of copper tubes in direct comparison to copper cups with the magnetic field applied along the axis of the shapes and at 30° from the axis. Copper tubes with a diameter of 50 mm, a length of 80 mm, and wall thickness of 1 mm were investigated to determine the time the tube shielded an axial 0.25 T field applied as a step function. A variety of locations within the tube and near the tube were analyzed. The field was then applied at an angle of 30° from the axis to investigate shielding effectiveness. One end of the tube was then capped, making a cup shape, and identical simulations were repeated. While this produced nontrivial changes at the edges, the shielding effectiveness at the center of the shape was not significantly affected by either the applied field angle (up to the 30° investigated) or the capping of one end of the tube. Shielding effects and focusing of the field due to induced currents in the copper can create a considerable impact on field sensors and the detection of moving conductive particles.

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1. Introduction

Shielding of magnetic fields is a well-known scientific and engineering phenomenon that has been characterized over many decades. It is useful in developing and enhancing new techniques for field sensing and, quite recently, characterizing hypervelocity projectiles.[1,2] The purpose of this work is to develop techniques using 3-D ALEGRA[3] simulations to aid in the development of new measurement techniques. Full 3-D ALEGRA simulations were used to understand the shielding effects of copper tubes in direct comparison to copper cups with the magnetic field applied along the axis of the shapes and at 30° from the axis. Shielding effects and focusing of the field due to induced currents in the copper can create a considerable impact on field sensors and the detection of moving conductive particles.

Copper tubes with a diameter of 50 mm, a length of 80 mm, and wall thickness of 1 mm were investigated to determine the time the tube shielded an axial 0.25-T field applied as a step function. A variety of locations within the tube and near the tube were analyzed. The field was then applied at an angle of 30° from the axis to investigate shielding effectiveness. One end of the tube was then capped, making a cup shape, and identical simulations were repeated. While this produced nontrivial changes at the edges, the shielding effectiveness at the center of the shape was not significantly affected by either the applied field angle (up to the 30° investigated) or the capping of one end of the tube.

2. ALEGRA Simulations

The transient magnetics mode of the multiphysics hydrocode ALEGRA was used with a Cartesian block mesh having four cells across the wall thickness of the copper tube and cup for the simulations with an axial field. A uniform B-field with a step function from 0.0 T to 0.25 T at 100 μs is applied via the boundary conditions of the mesh. In this work, the field direction is applied along the z-axis, thus the tube and cup are axially symmetric in the x and y direction about the z-axis for the axially applied field. For the applied field at 30° from the shape axis, the boundary conditions are maintained, and the tube/cup is rotated by 30° in the y direction. Consequently, the field is still tangent to the sides of the tube/cup at the x direction boundaries but not at the y direction boundaries, thus breaking the symmetry of the applied field. For this case of the rotated shape, the mesh has three cells across the wall thickness because the mesh space was increased to allow the rotation. A simulation was also performed for the axial field with the larger boundary conditions to check for consistency with the expansion of the boundary, and it was determined that the data were consistent. Each simulation was carried out for 3 ms.

2.1 Magnetic Shielding Produced by a Copper Tube

The 1-mm-thick copper-walled tube develops eddy currents to oppose any change in magnetic flux as the field is applied. Initially the inside of the tube remains at 0.0 T while the surrounding area is at 0.25 T. The field response along the centerline of the tube as a function of time is shown in Fig. 1. (All figures show the magnitude of the B-field and not a particular vector component.) As the eddy currents diminish due to the resistivity of the copper tube, the field encroaches within the confines of the tube. This "soaking-in" of the field takes about 3 ms to complete. This soak time is proportional to the electrical conductivity of the tube. While the field at the ends of the tube is not completely suppressed, the field inside the tube at a distance of about one-quarter of the length of the tube is nearly identical to the field at the center. Thus, the shielding response of the tube is quite uniform over at least 50% of the middle of the tube.

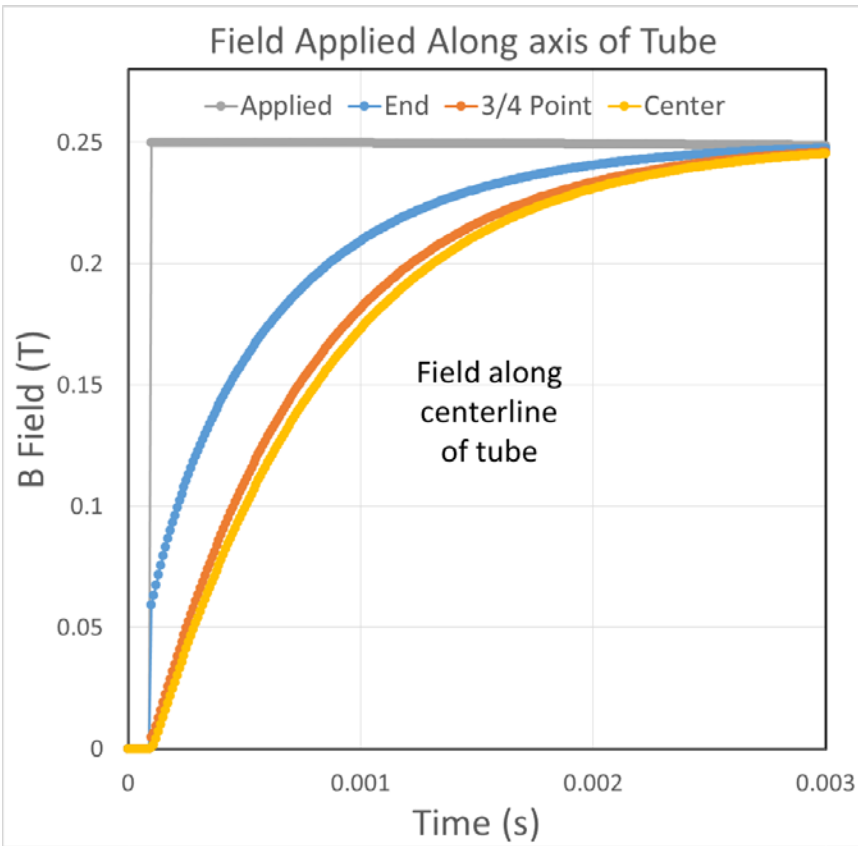

Fig. 1 Field response along the centerline of a copper tube

The field was also monitored within the tube wall along the length of the tube. In Fig. 2a, the shielding response within the tube wall at the midway point of the tube (labeled "Edge") is compared to the response at the center axis point (labeled "Center" in Figs. 1 and 2) and the response at the end of the tube (labeled "End" in Fig. 1, but labeled "Bottom" in Fig. 2 because that point will become the bottom of the cup once the tube is capped at one end). The response in the wall is very similar to that at the end of the tube, which allows a portion of the field to immediately fill the area.

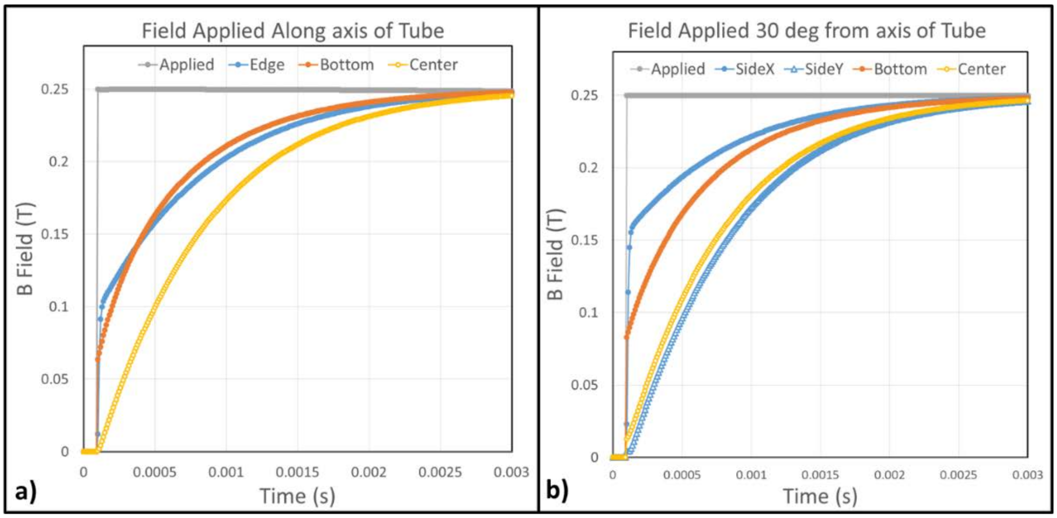

Fig. 2 Comparison of the response of a) axially and b) off-axis applied fields to a copper tube

By rotating the tube 30° in the y-direction, the end and the wall at the x-axis ("SideX") both allow larger fields to initially penetrate. However, the field in the wall at the y-axis ("SideY") trends closer to that of the field at the center of the tube as shown in Fig. 2b. This is consistent with the fact that a portion of the applied field is now normal to the tube surface at the y-axis, thus eddy currents are developed to oppose the flux through the conductive surface.

2.2 Magnetic Shielding Produced by a Copper Cup

The identical simulations for the capped tube or cup showed exactly what was expected: the shielded area within the tube extending to the end that was capped. Thus, approximately three-quarters of the inner portion of the structure is shielded from the B-field. While this may seem obvious, it is important to note that the response at the edge is unaffected, as shown in Fig. 3a (axial field) and 3b (30° off-axis field). In the off-axis applied field, the shielding response of the bottom, the side in the y-direction, and the center are essentially identical to each other, whereas the response along the side at the x-axis point is a repeat of the response of the tube.

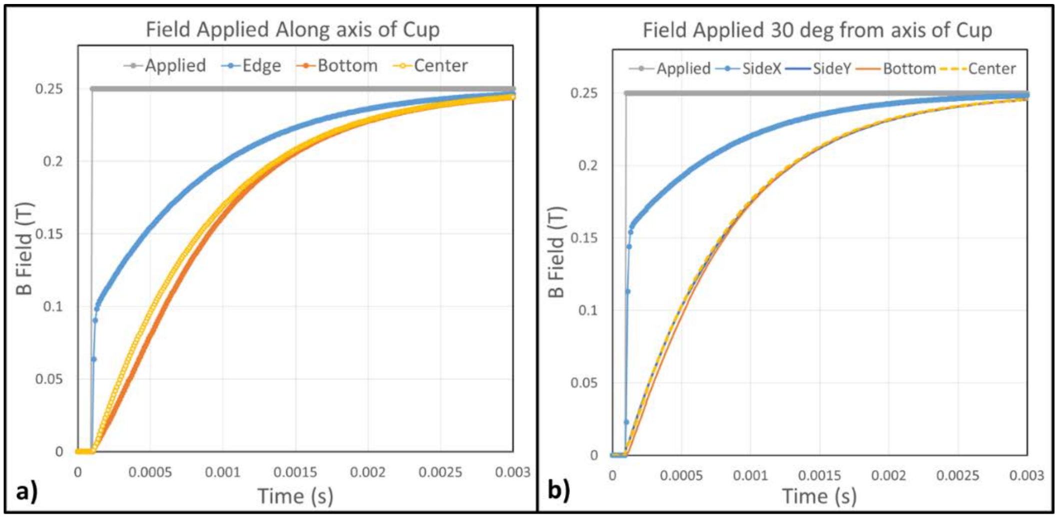

Fig. 3 Comparison of the response of a) axially and b) off-axis applied fields to a copper cup

2.3 Tube and Cup Comparison

The times that the shielding allows 80% of the applied magnetic field at various locations around the two shapes are listed in Table 1.

Table 1 Times when B-field surpasses 80% within the shielding (all times are in milliseconds)

Shape configuration	Side at x-axis	Side at y-axis	Bottom/End	Center
Tube axial	0.86	0.86	0.75	1.21
Tube 30°	0.49	1.21	0.71	1.13
Cup axial	0.92	0.92	1.31	1.27
Cup 30°	0.51	1.21	1.20	1.19

The distortion of the field around the shapes and the shielding effectiveness inside the object are more readily understood via a snapshot in time of the field map as shown in the side-by-side comparison of the tube and cup of Fig. 4. The slice shown is in the z-y plane at a simulation time of 500 µs (400 µs after onset of the field) for the off-axis applied field. Figure 4a corresponds to the tube simulations, and Fig. 4b corresponds to the cup simulations. The color map has red at 0.25 T and blue at 0.1 T on a log scale. A progression of the field as a function of time in lower-resolution images is shown in Fig. 5.

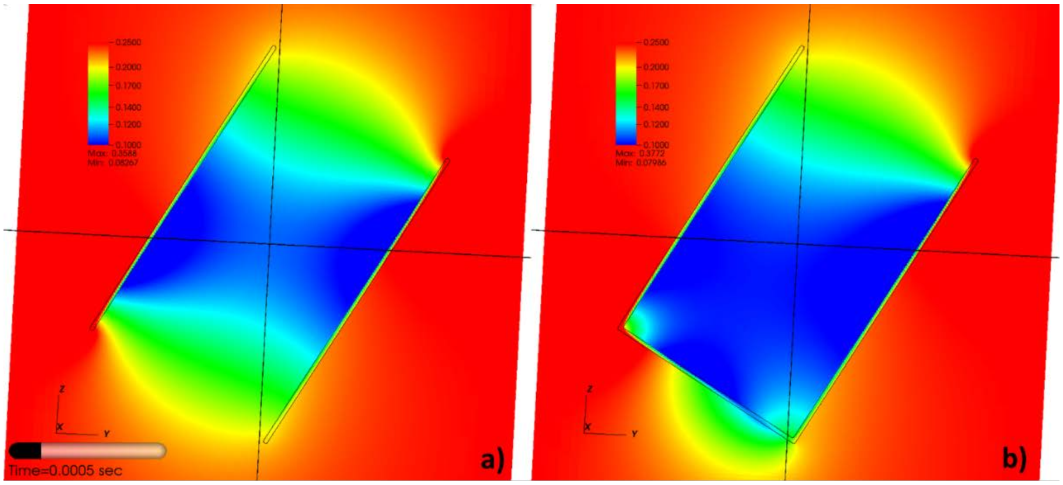

Fig. 4 Comparison of the shielding response of a) copper tube to b) copper cup with the field applied at 30° off-axis 400 μs after field application

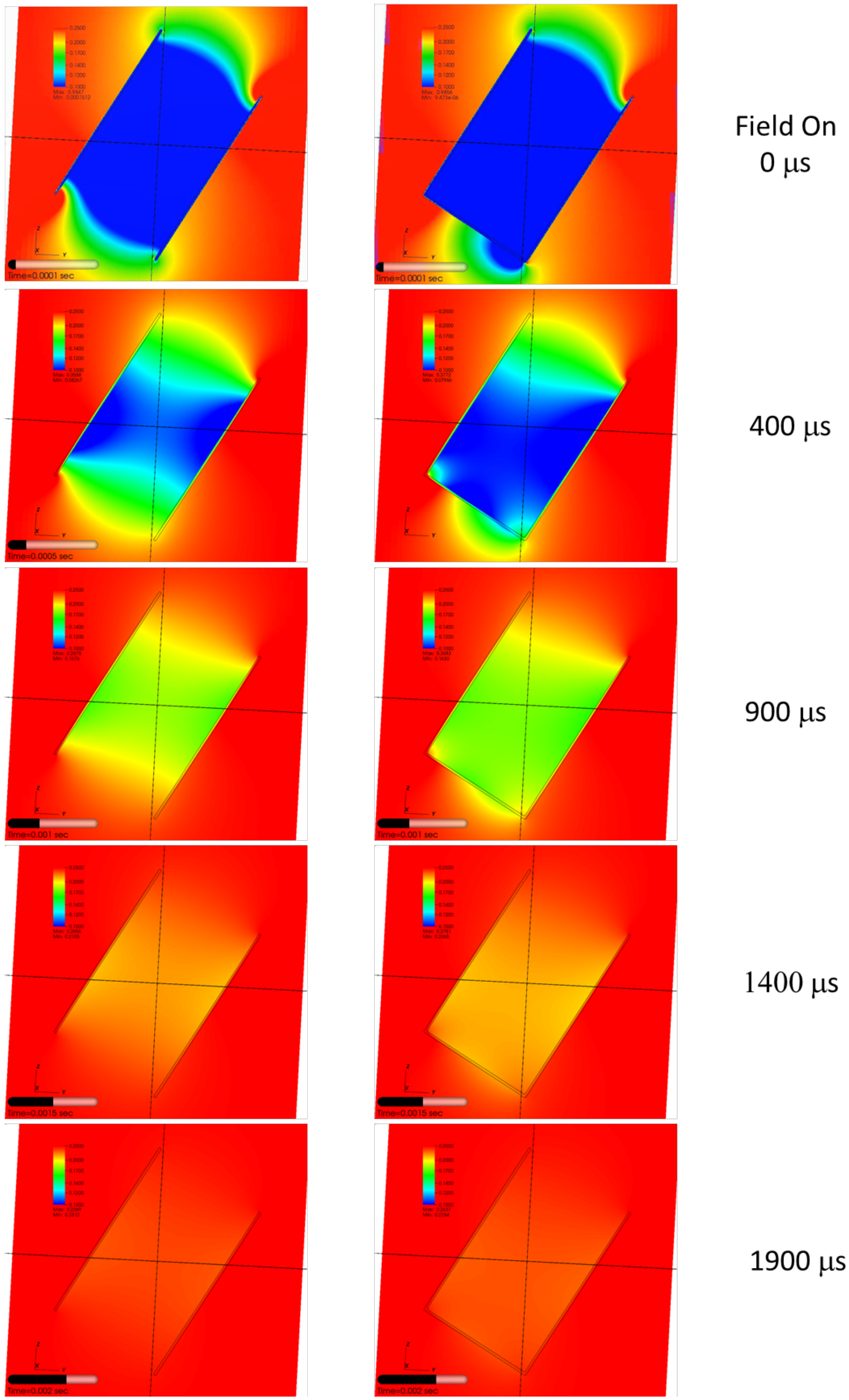

Fig. 5 Test image to determine effectiveness of image analysis algorithm

3. Conclusion

ALEGRA simulations in 3-D are proven to be a powerful tool in understanding the response of conductive materials in the presence of applied magnetic fields.

4. References

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List of Symbols, Abbreviations, and Acronyms

3-D	3-dimensional
ALEGRA	Arbitrary–Lagrangian–Eulerian General Research Applications

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
2 (PDF)	DIR ARL IMAL HRA RECORDS MGMT RDRL DCL TECH LIB
1 (PDF)	GOVT PRINTG OFC A MALHOTRA
13 (PDF)	ARL RDRL WM S SCHOENFELD RDRL WMP D LYON RDRL WMP A P BERNING S BILYK J CAZAMIAS M COPPINGER W UHLIG RDRL WMP D R DONEY M KEELE J RUNYEON M ZELLNER RDRL WMP E P SWOBODA P BARTKOWSKI