EDDY CURRENT SIMULATIONS FOR THE SSCL LOW ENERGY BOOSTER CAVITY

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ABSTRACT

Eddy currents are developed in the tuner of the Superconducting Super Collider Low Energy Booster (LEB) cavity during the LEB frequency sweep. The two main difficulties created by the eddy currents are excessive tuner–surface heating, and more important, a reduction in the time response of the tuner. We present a detailed analysis of the eddy currents for various tuner designs. The analysis has been done using 2D and 3D time–domain finite element codes: PE2D by Vector–Field and MSC/EMAS by The MacNeal–Schwendler Corporation. Non–linear analysis was performed utilizing B–H curves. The codes have been benchmarked analytically and by using measured data for different slotted pillbox structures.

INTRODUCTION

The Superconducting Super Collider (SSC) Low Energy booster (LEB) cavity is designed for frequency sweep of 47.5–59.8 MHz in approximately 20 ms. The frequency sweep is achieved by varying a biased magnetic field perpendicular to the rf magnetic field inside the ferrite–filled cavity tuner. Figure 1 is a 3D view of the LEB turner. One of the most important aspects of the LEB cavity design is control of the eddy currents developed in the tuner during this frequency sweep. the two main difficulties created by the eddy currents are excessive tuner–surface heating, and more important, a reduction in the response time of the tuner to a triggered control signal. The eddy currents created on the tuner metallic surface can be reduced in two ways: by slotting the surface, which increases their path length, or by equivalently increasing the material electric resistivity. The second approach of using a closed–shell tuner with high resistive alloy is more mechanically suited to the LEB cavity if the ferrites are liquid–cooled. This structure has the electrical disadvantage of reducing the frequency response bandwidth to about 150 Hz for the available resistive alloys. A slotted tuner, on the other hand, is mechanically more complex but has a frequency response bandwidth in excess of 2000 Hz, which is better for the cavity control loop.

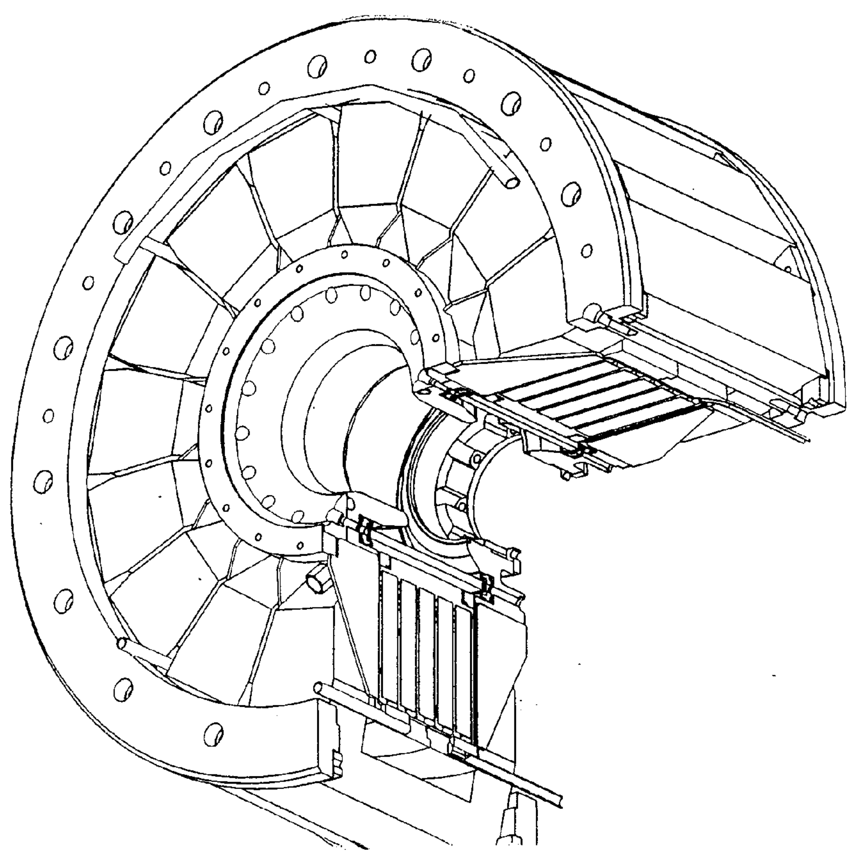

Figure 1. LEB Tuner Design

This paper is divided into four sections. The first presents the results of an analytical treatment of the eddy currents developed in an infinitely long metallic cylindrical shell. We show that contrary to the widely held belief that the penetration of magnetic field into metals can be described in terms of a single parameter, the skin depth–in our case the relevant parameter–is the square of the skin depth divided by the shell radius. The second section presents a numerical analysis of a closed–shell tuner design. The analysis has been done using PE2D, which is a time domain, finite element 2D code. Utilizing this code we design a tuner made of a Ti–6Al–4V alloy that has a high electrical resistivity as well as very good mechanical strength. This alloy yields a substantial reduction in eddy currents and two orders of magnitude increase in frequency bandwidth compared with a copper tuner. The third section is a numerical analysis of slotted tuner design. The analysis has been done using a 3D time domain finite element code, MSC/EMAS by MSC. It shows, contrary to another widely held belief, that eddy current problems can be analyzed by the quasi–stationary approximation that the rate of penetration of the magnetic field into the tuner through the slots depends on the displacement currents across the slot. The final section is a short summary.

EDDY CURRENTS IN A METALLIC SHELL

First we review the results of long thin metallic shell inside a long solenoid.[1,2] The geometry of this setup is described in Figure 2. The axial magnetic field in region I is given by

$$B_z(t) = \mu \, \Delta_c \, \delta_s \exp(-\delta_s t) \int \exp(\delta_s \tau) J(\tau) d\tau$$

and the eddy current in the metallic shell is

$$J_{eddy} = -J \, \Delta_c/\Delta_s + \Delta_c/\Delta_s \delta_s \exp(-\delta_s \tau) \int \exp(\delta_s \tau) J(\tau) d\tau$$

The results in equations 1 and 2 have been obtained assuming a spatially constant current density drive J. The parameter δ_s is defined by

$$\delta_s = 2 / (\mu \, \sigma_0 \, \Delta_s R_1)$$

where σ_0 is the shell conductivity. The parameter δ_s in equation 3 measures the inverse of the magnetic diffusion time through the metallic shell. A tuner design with low eddy currents and fast magnetic time response will be characterized by the inequality $\delta_s T_{ch} >> 1$, where T_{ch} is the characteristic time scale of the drive current J. the maximum eddy current obtained for this time scale is

$$J^{max}{}_{eddy} = J_0 \, \mu \, \sigma_0 \, \Delta_c \, R_1 / (2T_{ch})$$

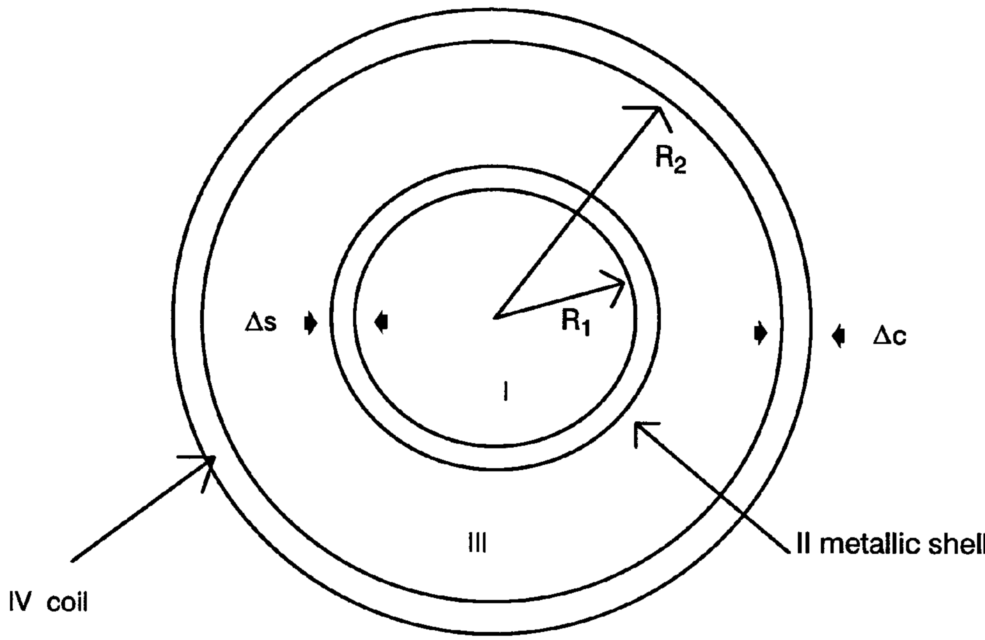

Figure 2. Infinitely Long Metallic Shell in Solenoidal Magnetic Field.

For equal heating rates of the solenoid and the metallic shell we estimate the shell conductivity $\sigma_0 \cong 5 \times 10^5$ s/m, which is two orders of magnitude lower than copper. The Ti–6Al–4V alloy with conductivity of 5.8×10^5 s/m makes it a good candidate for a closed–shell LEB tuner.

The cavity rf frequency program is achieved by biasing the ferrite. The relationship between this magnetic field and the current drive determines the cavity response to a control signal. It is common to quantify the response in the frequency domain by its 3–dB bandwidth. Fourier decomposing eq. (1) we obtain

$$B_z(\omega) = \mu \Delta_c J(\omega) \; / \; (1 + i\Delta_s / (\lambda_s^2 \; / \; R_1))$$

where $\lambda_s = (2/\omega\mu\sigma_0)^{1/2}$ is the standard skin depth definition. It can be seen from equation 5 that the parameter which determines the magnetic penetration through the shell is given by the square of the skin depth divided by the shell radius. The 3–dB frequency bandwidth is given by

$$\Delta_f = 1 \; / \; (\pi \, \mu \, \sigma_0 \, \Delta_s \, R_1)$$

For a 5 mm thick titanium alloy shell, this translates into a bandwidth of 292 Hz, about two orders of magnitude greater than for a copper shell.

NUMERICAL ANALYSIS OF A CLOSED SHELL TUNER

Using the analytical results above as a guide, we numerically simulated the closed shell LEB tuner. We used the 2D time domain finite element code PE2D by Vector Fields. This code is also capable of handling materials with a nonlinear B–H curve. The simulated tuner geometry is shown in figure 3, where the scale is in centimeters. The simulation was done on an old version of the tuner. Higher voltage requirements required us to add one more ferrite ring. The drive current required to follow the frequency program is described in figure 4. The current reaches approximately 17,000 At at 50 ms, then drops in 30 ms to approximately 4000 At to the end of the cycle. This curve has been determined in two stages. At first the code was run in the steady state mode with various currents to establish a relation between the drive current and rf permeability given by the frequency program. In the second stage the transient analysis with nonlinear materials is done. The maximum eddy current is developed at the top of the tuner, where its two half shells are joined (see figure3.) Figure 4a describes the magnitude of the eddy current at this point. the deviation from the smooth curve is of numerical origin and relates to the way the code handles the derivative of the drive current. The maximum eddy current obtained is 60 A/cm_2 at 17 ms from the beginning of the cycle. In comparison the maximum eddy current for a copper tuner is about 2700 A/cm^2 . The thermal power, averaged on a cycle, developed at this point is about 0.18 W/cm^3, which can be handled without much difficulty by the tuner internal coolant.

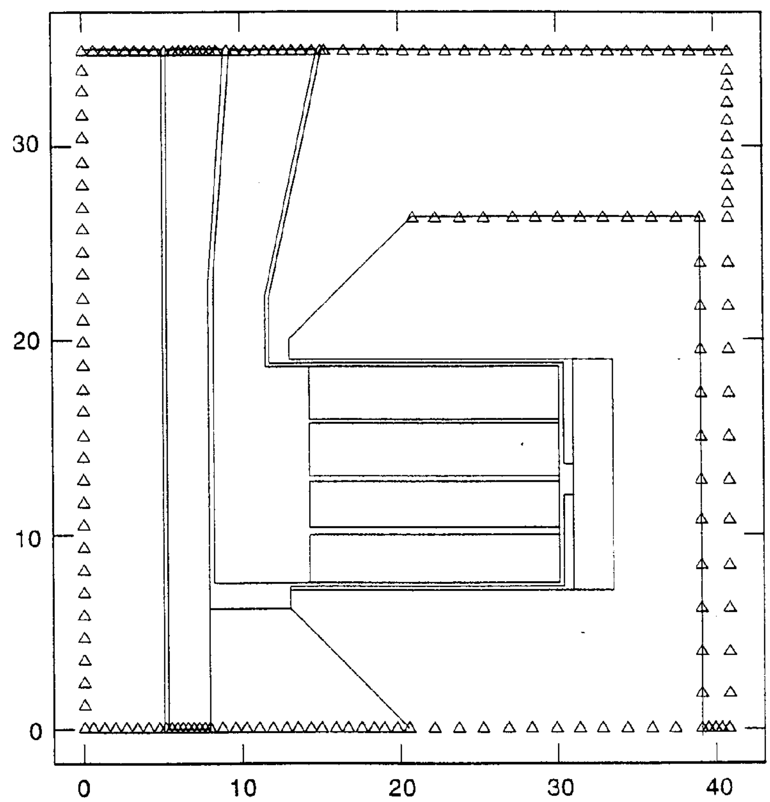

Figure 3. Tuner Geometry for PE2D

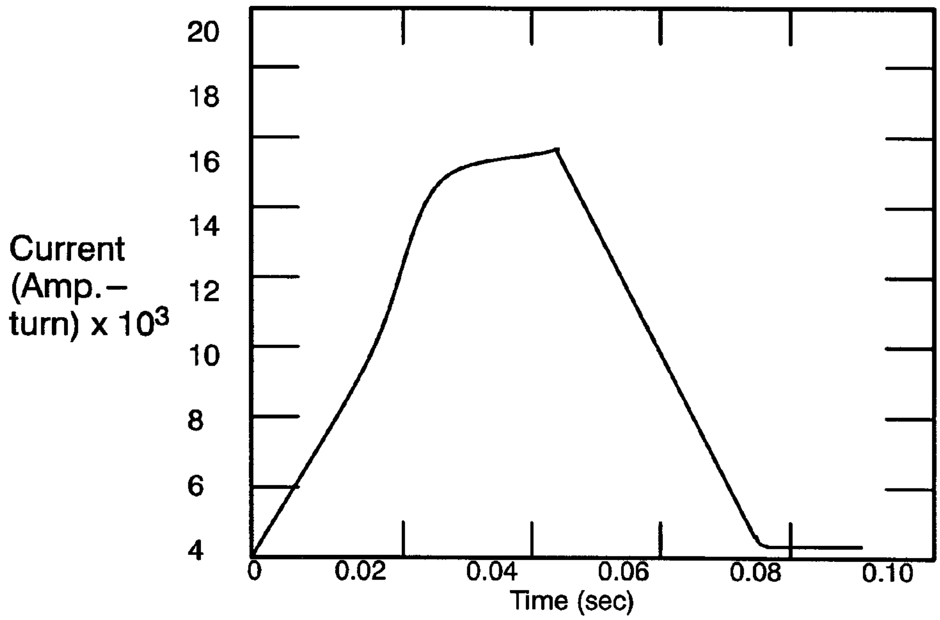

Figure 4. Tuner biased Current.

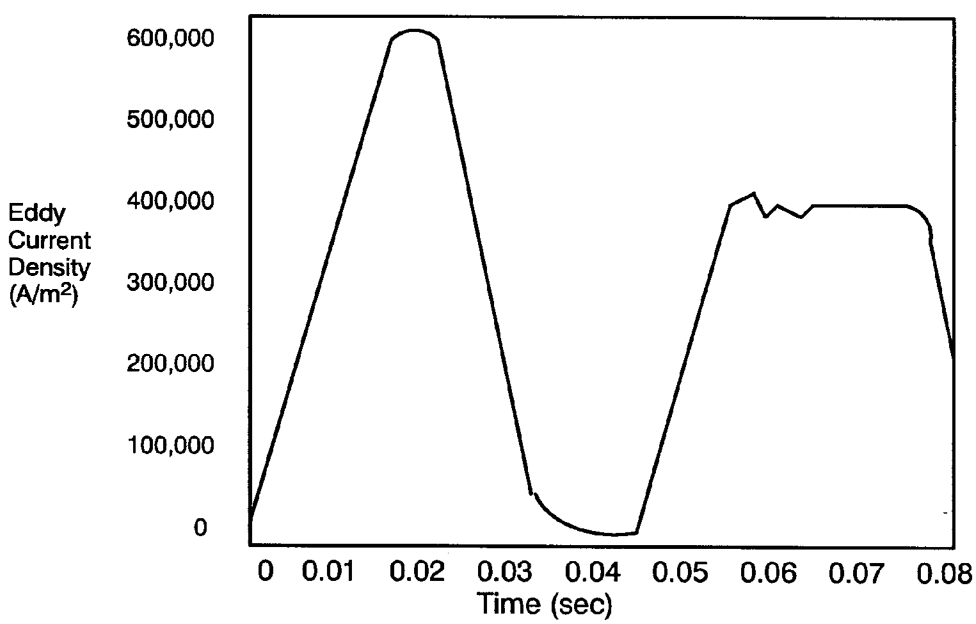

Figure 4a. Eddy Current in Titanium Tuner.

The analysis of the tuner frequency response is done with the 2D frequency domain option of MSC/EMAS. MSC/EMAS is a 3D time and frequency domain, finite element, electromagnetic code. Like PE2D, it is able to handler materials with nonlinear B–H curves. We find that the frequency response is varied across the tuner cross section with the minimum bandwidth at the bottom of ferrites. The magnetic field vs. frequency at this location is shown in figure 5. It can be seen from the figure that the 3–dB bandwidth is about 140 Hz, considerably lower than the 292 Hz expected from an infinitely long metallic shell. The discrepancy corresponds to the relatively slow magnetic penetration through the side walls of the tuner. To confirm the above results we benchmarked the code by using measured data of the magnetic field at various locations inside a closed stainless steel can. Figures 6 and 7 are the frequency response of the amplitude and phase of the magnetic field at the center of the can. The experiment and simulation are within the experimental error of about 0.3 dB and 2.0 deg. The narrow frequency response bandwidth led us to abandon the closed shell tuner and to design a slotted tuner instead.

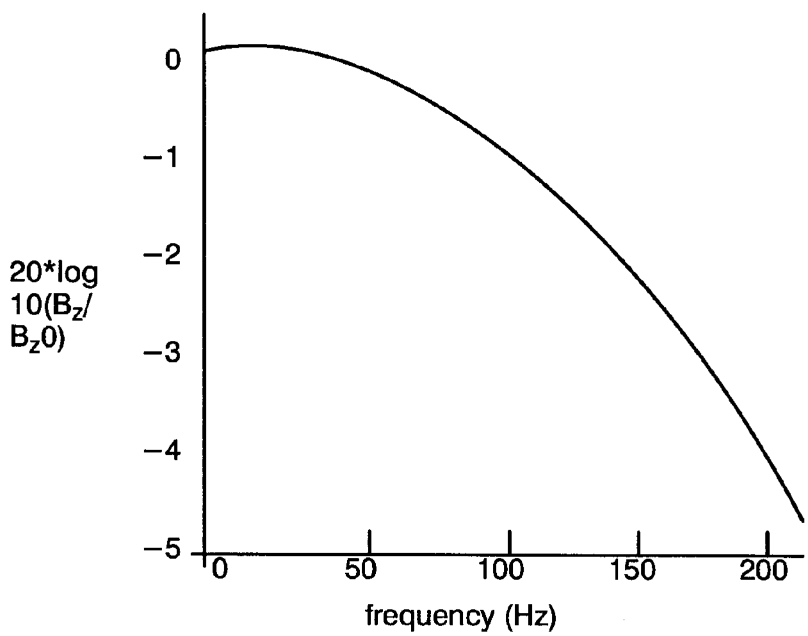

Figure 5. Frequency Response of Titanium Closed Shell Tuner.

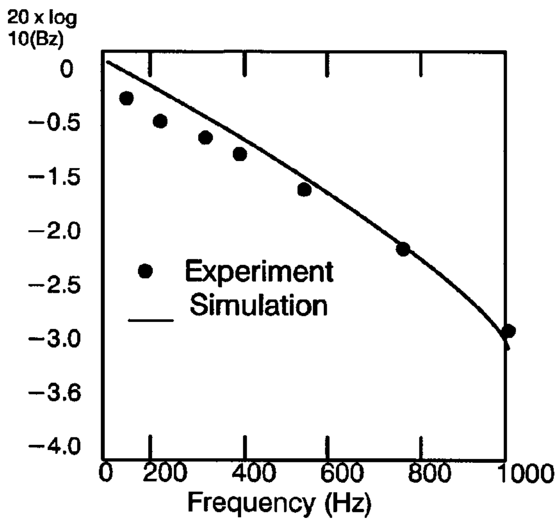

Figure 6. Magnetic Response of Close Can Amplitude

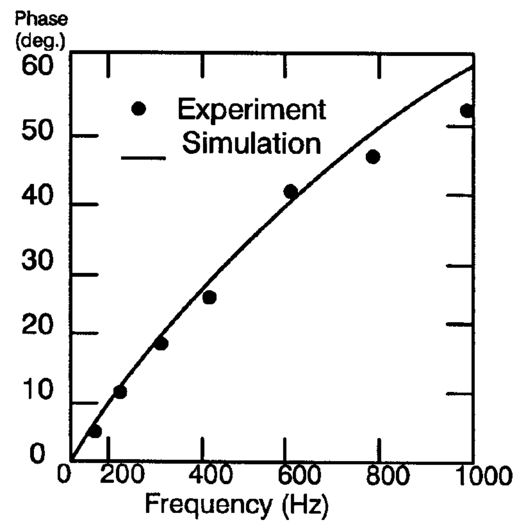

Figure 7. Magnetic Response of Close Can Phase.

NUMERICAL DESIGN OF A SLOTTED SHELL TUNER

The analysis of the closed shell tuner in the last section was performed using the quasi−static approximation, which neglects the displacement current in Maxwell's equations. Using this approximation for the 3D problem of a slotted tuner yielded a false solution in which the slots had a very small effect on the rate of magnetic penetration into the tuner. The need for the displacement currents is illustrated in figure 8. As the eddy currents approach the slot discontinuity, they charge its surface. The charges create electric fields, which oppose the small internal field in the metal and enforce the currents to change direction and bypass the slot.[3] To confirm this assumption we compared the numerical simulation with measured results for a stainless steel can with various numbers of slots. Figures 9 and 10 describe the magnetic frequency response of a can with 8 slots. The simulation results are within the experimental errors of 0.1 dB and 1 deg. Encouraged by these benchmark results, we designed a slotted LEB tuner. The tuner is made of 3 mm stainless steel with 16 5−mm radial slots. The slots are filled with G10 compound (dielectric material) to contain the coolant. The magnetic frequency response of this tuner is shown in figures 11 and 12 with a 3 dB bandwidth, which exceeds 2000 Hz. Figure 13 describes the eddy current flow across the tuner surface around a slot for a 250 Hz frequency drive. Notice the small elongated elements that must be defined around the slots for the code to converge properly.

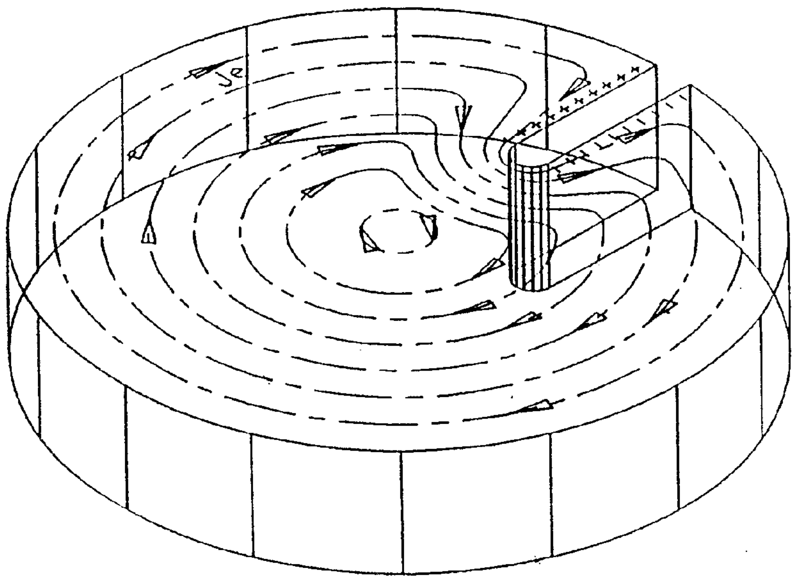

Figure 8. Eddy Currents Around a Slot.

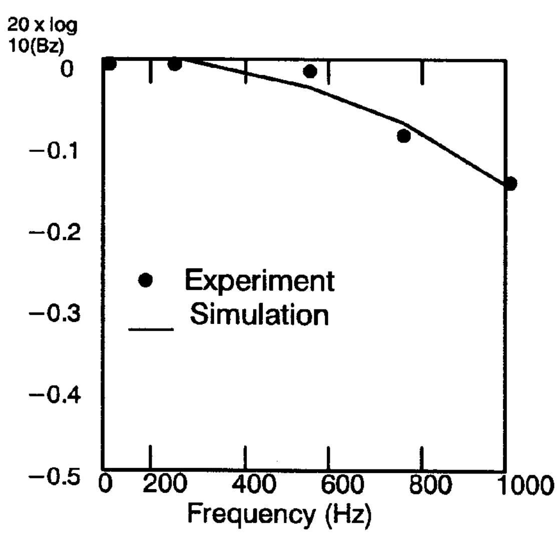

Figure 9. Magnetic Response of Slotted Can (8 Slots) Magnitude

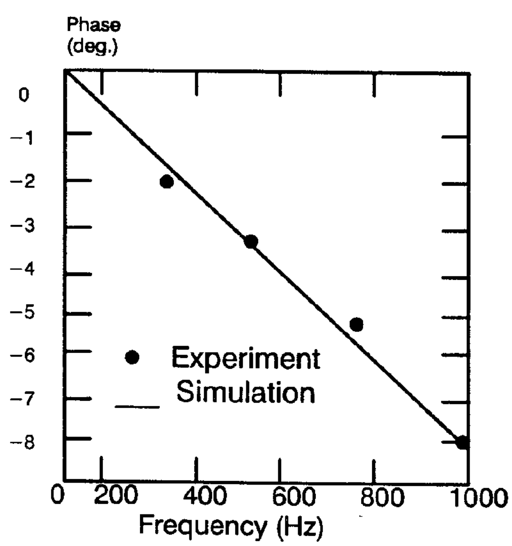

Figure 10. Magnetic Response of Slotted Can (8 Slots) Phase.

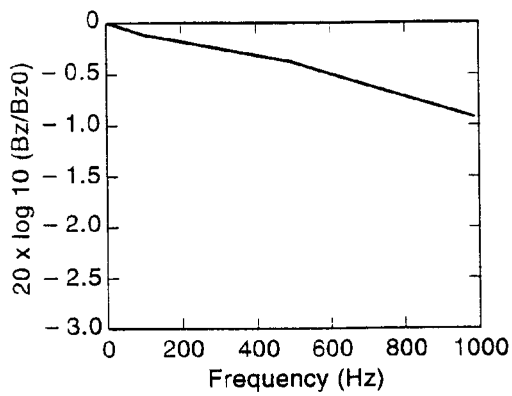

Figure 11. Magnetic Response of LEB Tuner (16 Slots) Magnitude

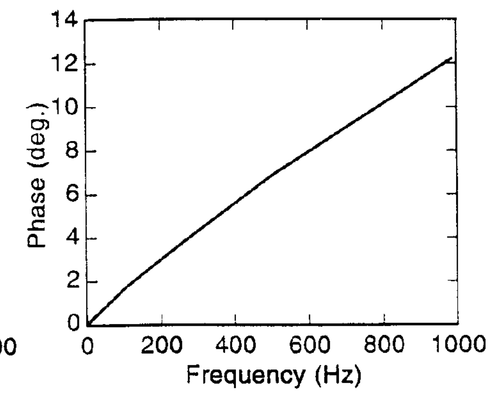

Figure 12. Magnetic Response of LEB Tuner (16 Slots) Phase

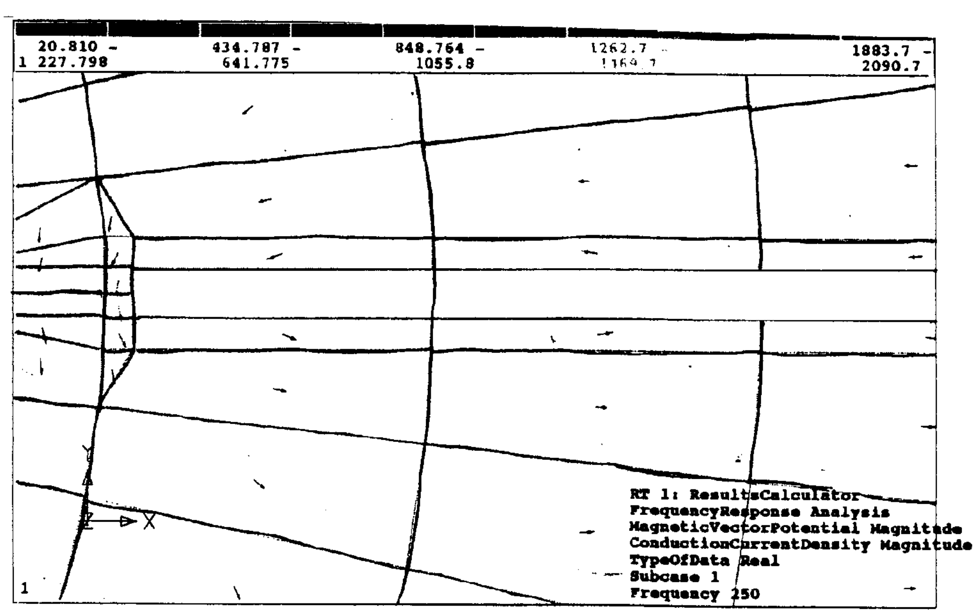

Figure 13. Eddy Current Around a Slot in the LEB Tuner.

CONCLUSION

We present numerical simulations of two LEB tuner designs. The surface heating due to the eddy currents is controlled in both schemes. The magnetic field frequency response of the closed shell tuner is only marginally acceptable. this leads to the slotted tuner design, which is mechanically more complex, but has the wide bandwidth required for the control system.

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