Modeling Low Frequency Magnetic Field Shielding using the Locally Corrected Nyström Method

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***Abstract*—The problem of magnetic field penetration into a conductive enclosure due to a low frequency loop transmitter is considered using simulations and experiment. The problem is relevant for electromagnetic shielding, through bunker communications, through conductor imaging, and several related problems. The primary difficulty lies in the multiple spatial scales due to the large wavelengths in the exterior and interior air regions in contrast to the short wavelengths in the highly conductive shell region. Although analytical solutions are possible for spherical shields and other specific geometries, determining the penetration through realistic conductive shields requires a numerical approach. Typical finite element methods can be employed to the shielding problem, however, appropriately meshing the enclosure and the air regions can be difficult when the skin-depth and wavelength in the shell are much smaller than the dimensions of the enclosure. To alleviate the multi-scale and near-field nature of the problem, a high-order locally corrected Nyström scheme is utilized to solve a surface integral equation based on an Augmented Müller formulation. The Nyström-SIE method is ideally suited for shield modeling due to the low surface area to volume ratio of the shield and the exponential convergence properties of the code. To validate the theoretical predictions from the model an experiment using two loop antennas inside and outside a 1.2 m aluminum cube of 3 mm thickness is conducted. It is shown that the experimental results agree with numerical predictions.**

I. INTRODUCTION

The penetration of electric and magnetic fields through conductive media is highly relevant for electromagnetic compatibility, shielding, and imaging applications. The required shielding materials and geometry are strongly dependent on the frequency of operation, the type of source, and specific application. Low frequency electric fields, also known as quasi-electrostatic fields, can be shielded using a Faraday cage setup which is essentially a metal cage with apertures that are much smaller than the wavelength of the incident signal. Low frequency magnetic fields, also known as quasi-magnetostatic fields, require either a mu-metal shield or high conductivity material with extremely good electrical contact at all seals. At higher frequencies the electric and magnetic fields are coupled and a combination of the aforementioned techniques can be utilized to shield against electromagnetic radiation. For the purposes of this work, the effectiveness of highly conductive and non-magnetic materials are considered for magnetic shielding with a near-field loop antenna.

The physical mechanism of shielding quasi-static magnetic fields is via the formation of induced conduction currents. The incident magnetic field will induce Eddy currents on the conductive shell that will in turn, by Lens's law, be forced to cancel the incident magnetic flux. Thus, based on the geometry of the conductive shield the permissible flow path of induced currents can dramatically alter the magnetic shielding effectiveness SE_H of a conductive enclosure. For instance, a spherical shield will have a current profile that smoothly varies from pole to pole of the shield. However, a conductive box with sharp corners and flat faces will force the induced currents to flow close to the edges of the box. Additionally, the type of source used can dramatically alter the shielding effectiveness. Most analytical solutions focus on a homogeneous magnetic field, which is effectively the same as a plane wave in the magneto-static limit. However, for a local near-field source, the spatial dependence of the fields as well as the effective wave impedance is dramatically different than that of a plane wave and analytical solutions are usually difficult.

Although SE_H can be analytically determined for selected shield geometries and sources [1], an accurate measure of SE_H for a complex conductive shield and local source requires a numerical approach. In this work, a high-order Nyström code is utilized to model the shielding effectiveness of a cubic aluminum enclosure. The following section describes the numerical model along with experimental validation.

II. MODEL AND EXPERIMENTAL VALIDATION

The numerical model employed in this work solves a surface integral equation based on the Augmented Müller formulation of Maxwell's equations with discretization using the locally corrected Nyström (LCN) method. The LCN method has the specific benefits of being a high-order method with exponential

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error convergence for electromagnetic scattering problems. Specific details of the numerical method is described in [2].

In order to validate the results of the simulations, a shielding experiment was performed in an urban setting. Specifically, the shielding effectiveness of a cubic aluminum box was determined by placing a loop receiver inside the box and transmitting loop outside the box. The aluminum box had sides of length 1.2 meters and a 3 millimeter shell thickness. The transmitter is considered to be at the origin of a Cartesian coordinate system with the loop normal oriented along the y-axis. The geometry of the experimental setup is shown in Figure 1.

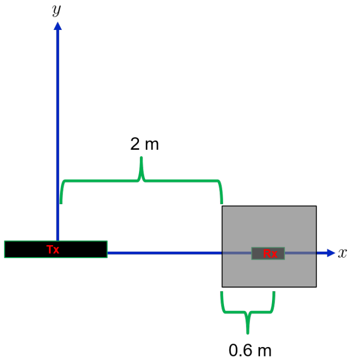

Fig. 1. Top-down view of experimental design of aluminum box shielding experiment with one loop transmitter and one loop receiver.

The frequencies considered in this experiment are between 1 kHz and 10 kHz since the thickness of the box is between one-half to two skin depths at these frequencies and appreciable penetration is expected to occur. Since these frequencies are in the audible spectrum, the transmitting loop was driven by a standard audio amplifier. The transmitter utilized a very basic design and simply consists of 10 winds of copper wire to build a 1 meter diameter loop source. The receiving antenna system utilizes a more sophisticated design and is based on the AWESOME VLF receiver system. The specifications of receiver hardware is described in detail in [3].

The transmitting format consists of a repeating frequency ramps from 0 to 10 kHz that last 5 seconds each. Representative spectrograms of the incident and penetrating fields are shown in Figure 2. As shown, the incident field has considerably high SNR and the penetrating field inside the box is weak but clearly visible on the spectrogram. The weaker CW signals at 20 kHz and 25 kHz are from distant Navy VLF transmitters, however, these signals do not interfere with the frequency band of the local transmitter.

In order to compare the modeling results with the simulations, the measured magnetic field at the receiver location was measured before and after the presence of the aluminum shield. The ratio of the penetrating fields (with shield) to the incident fields (no shield) thus determines the penetration loss due to the aluminum box. A comparison of the simulation and experiment is shown in Figure 3. As shown, the locally corrected Nyström code matches well with the experimental data of shielding effectiveness.

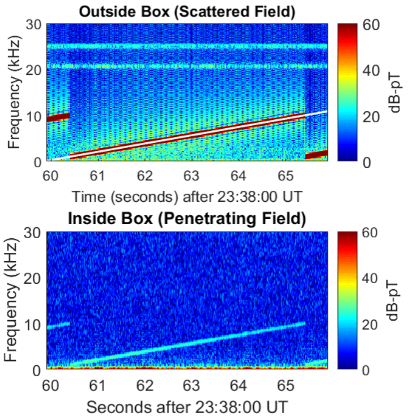

Fig. 2. Spectrogram of incident magnetic field (above) and shielded magnetic field (below).

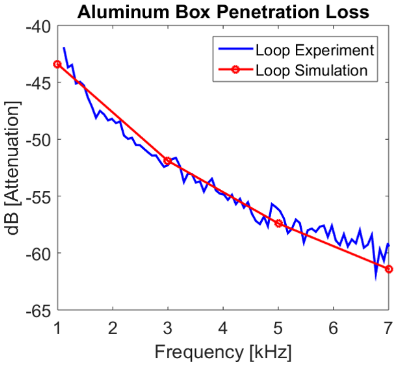

Fig. 3. Comparison of experimental data and LCN simulation for magnetic field penetration into an aluminum box.

III. CONCLUSION

The magnetic field shielding effectiveness of a cubic aluminum enclosure is investigated using numerical simulations and experiment. The numerical model employs a high-order locally corrected Nyström solution to the augmented Müller surface integral formulation of Maxwell's equations. Simulations are shown to match with the experimental data.

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