The Effects of a Superparamagnetic Ground on the EMI Response of a Target

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Abstract: Soil's electromagnetic properties adversely affect the performance of EMI sensors and if conditions are severe enough, render them useless. A simple circuit model is often used to express the electromagnetic induction response of a target analytically. This analytic model produces a response function that contains unique characteristics based on the target's electromagnetic properties. This work uses the analytic model for validation then investigates the effects of a super-paramagnetic ground on the response of a target.

Keywords: EMI, super-paramagnetic, AC/DC module, landmine, UXO.

1. Introduction

Electromagnetic induction (EMI) sensors have a long history of success in finding visually obscured metal objects [1]. **Figure 1** shows a world map of countries that are affected by landmines. Many of these countries are in the tropical region where soil conditions are highly weathered producing strong magnetic properties [2]. Soil's electromagnetic properties can adversely affect the performance of EMI sensors and if conditions are severe enough, render them useless. Thus understanding and quantifying the effects of magnetic soils on EMI sensors is required.

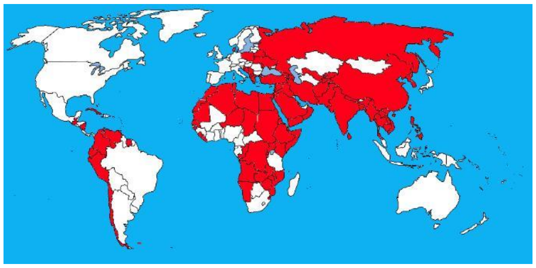

Figure 1: *World map showing the countries affected by landmines in red [3].*

1.1 Super-paramagnetic Ground

Mineralized soil has two properties that contribute to a target response in the very low and low frequency spectrum. The electrical conductivity gives rise to eddy currents which produce a measureable response. The magnetization of the material also produces a measureable response. Das has shown that the magnetic response from soil largely dominates the electrical response [4]. The response of the magnetic soil has been found to be accurately explained if the magnetic susceptibility of the soil is allowed to vary with frequency. A well-established model for a super-paramagnetic ground assumes a log-uniform distribution of magnetic relaxation constants resulting in a magnetic susceptibility of the form [5]:

$$\chi_{(\omega)} = \chi_{dc}\left(1 - \frac{1}{\ln\left({}^{\tau_2}/_{\tau_1}\right)} \cdot ln\frac{i\omega\tau_2+1}{i\omega\tau_1+1}\right) \qquad (1)$$

where χ_{dc} is the static (dc) value of the MS, ω is the angular frequency, $i = \sqrt{-1}$ and τ_1 and τ_2 are the lower and upper bounds of the magnetic relaxation time constants, respectively. The magnetic susceptibility is plotted with respect to frequency in **Figure 3**.

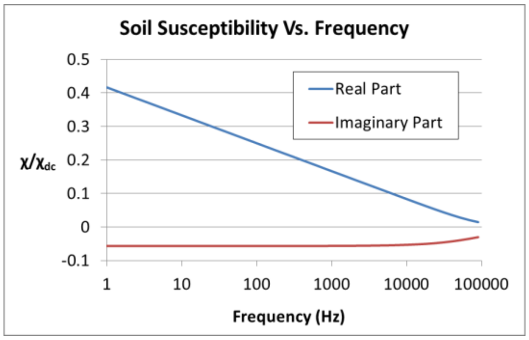

Figure 2: *Model used for frequency dependent magnetic susceptibility given by Equation (1).*

2. Use of COMSOL Multiphysics

The magnetic fields interface from the AC/DC module was used to compute the magnetic fields and induced currents by solving Maxwell's equations in the entire simulation domain. Maxwell's equations are solved in COMSOL using the following formulation:

$$(j\omega\sigma - \omega^2 \varepsilon_0 \varepsilon_r) A + \nabla \times (\mu_0^{-1} \mu_r^{-1} B) = J_e$$

$$B = \nabla \times A$$

where ω is the frequency, σ is the conductivity, J_e is the external current density, B is the magnetic flux density, A is the magnetic vector potential.

2.1 Simulation Domain

The simulation domain is depicted in **Figure 3**. A spherical domain was chosen as it fits the shape of the magnetic fields well, although a cylinder domain could also have been used. The sphere has a thin shell placed on the outside boundaries which are used to place the infinite element domains. The ground half-space serves as the bottom half of the sphere.

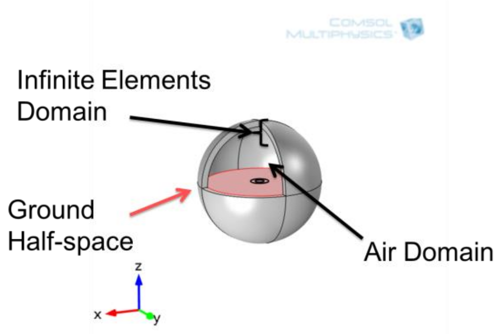

Figure 3: *The simulation domain.*

An EMI sensor is modeled as concentric transmit and receive coils as depicted in **Figure 4**. The axial symmetry of the coils and target begs for a 2D axisymmetric model, but due to the ground half-space a 3D model is required. Convergence issues arise in 3D models when the conductivity of air is set to 0 S/m. Therefore a non-zero value is required to provide numerical stability for the iterative solver. The conductivity of air was set to 1 S/m which produces negligible effects because the skin depth is significantly larger than the simulation domain for our chosen frequency range.

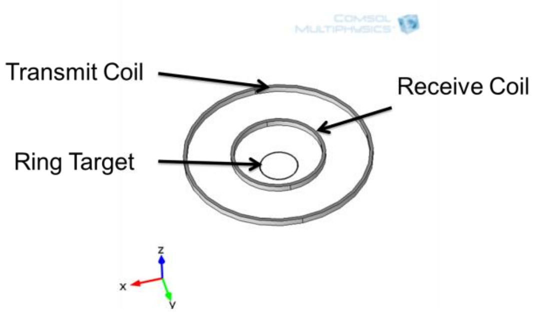

Figure 4: *Transmit and receive coils with a ring target a 3cm depth.*

2.2 Boundary Conditions

A magnetic insulation boundary condition is required on the exterior boundaries of the model in order to form a closed system. This boundary condition sets the tangential components of the magnetic vector potential to zero at the boundary:

$$n \times A = 0$$

Sufficient distance is required between the magnetic insulation boundary condition and the model in order for the boundary condition to produce negligible effects. One way to approach this is to extend the simulation domain "far enough" that the exterior boundary condition becomes negligible. While this works, it greatly increases the number of mesh elements and computational resources required to solve the problem. A more efficient way to attack this problem is to use an infinite elements domain. In our application, this domain takes incident magnetic fields on the interior boundary and scales them towards infinity at the exterior boundary.

2.3 Coil Domains

The transmit and receive coils of an EMI sensor typically have many turns, sometimes on the order of hundreds. Unfortunately this poses an issue during geometry creation and meshing resulting in the need for large computational resources. COMSOL has two built in coil domains, single-turn and multi-turn, that greatly simplify the geometry required to model such complicated coils.

The transmit coil was modeled using the multi-turn coil domain which allows the number of turns, conductivity, cross-sectional area of the wire, and other material properties to be specified. The number of turns was set to 50, the conductivity to that of copper, 6e7 S/m, and the wire gauge to AWG 28. The excitation voltage amplitude was set to 10 V.

The receive coil was modeled using the multi-turn coil domain. The number of turns was set to 25, conductivity to 6e7 S/m, and the wire gauge to AWG 28. Since the voltage of the receive coil is usually the quantity measured in an EMI sensor, a current excitation of 0 A was used.

2.4 Super-paramagnetic Ground

The lower half-space of the sphere was given a frequency dependent magnetic susceptibility. COMSOL allows for any input value to take the form of an equation assuming the variables are all defined. In order for this condition to be met, the study must specify both a frequency and a DC magnetic susceptibility value. It has been found that the DC magnetic susceptibility can vary by approximately 10% over ~12m^2 area. A fourth order random noise function was used to scatter the DC magnetic susceptibility value over the soil half-space. While a third order would produce enough for the volumetric variability, a fourth order was required to allow the observer to randomize between simulations. **Figure 5** shows the volumetric randomized magnetic susceptibility in the soil half-space.

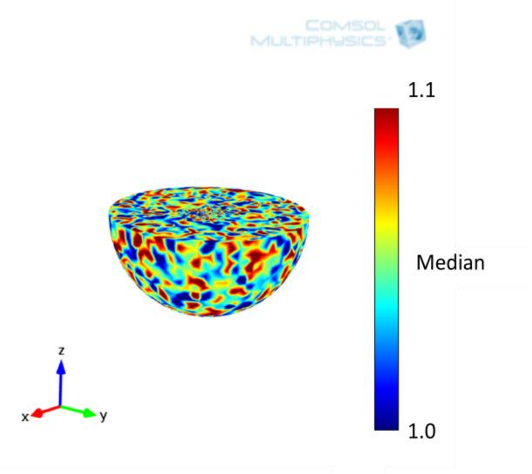

Figure 5: *Modeled magnetic soil half-space with a volumetric variability in magnetic susceptibility of 10%*

2.5 Meshing

The ring target was the smallest domain so the mesh began there. A free tetrahedral mesh was used with a minimum element size specified at .04 cm which was enough to resolve the curvature. While a boundary layer mesh provides a better means to resolve the current, it caused issues with meshing the other domains. Since the frequencies in the study are less than 100 kHz the skin depth was still resolved using the tetrahedral mesh. Tetrahedral mesh was used for all the remaining domains except for the infinite elements domain. In order to properly map the inner coordinates to the exterior boundary, a swept mesh is required. A distribution was used to make sure the swept domain contained 5 elements between the interior and exterior boundaries. **Figure 6** depicts the meshed transmit and receive coils.

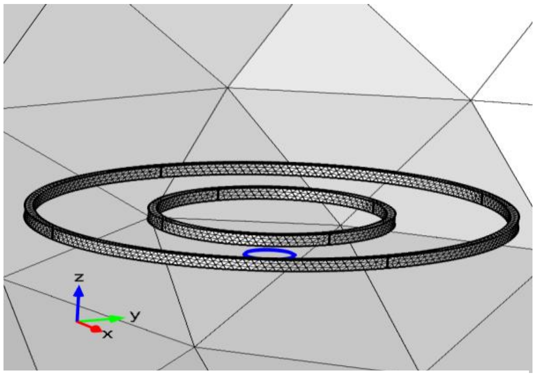

Figure 6: Tetrahedral meshing of transmit and receive coils.

3. Model Verification

Model verification is an important step to ensure that the model environment is properly set up and that the physics is correct. A simple circuit model is often used to model the response of a ring target measured by a transmit and receive coil [1]. A ring of AWG 22 wire with a 3cm loop diameter has a single peak in the imaginary portion of the response at 10.1 kHz. **Figure 6** depicts the COMSOL results for this ring. The imaginary peak is located at 9.5 ± .5 kHz which is in agreement with both the theoretical value and with Scott's measured value [6]. The error in the measured value was determined by finding the minimum frequency step size before solution oscillation occurred. A mesh refinement study was also performed to make sure the mesh did not affect the solution.

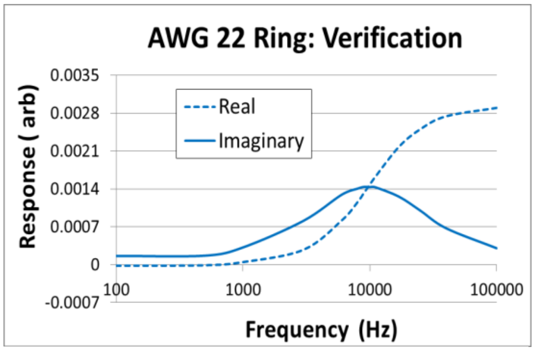

Figure 6: *Measured response function from COMSOL simulation used to validate the model.*

4. Results and Discussion

After the model was verified the soil-half space was added to the model. The same frequency sweep was performed and the results are shown in **Figure 7** for various levels of magnetic soil. The soil levels are defined by the European Committee for Standardization. It was found that the real portion of the response was affected the most by the super-paramagnetic ground. As frequency increases the effects of the soil begin to diminish as expected since the real and imaginary components of the frequency dependent magnetic susceptibility approach zero with increasing frequency.

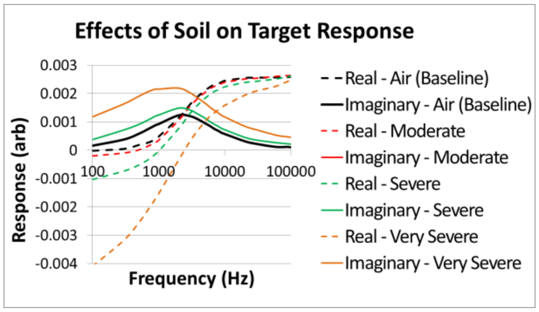

Figure 7: *Measured EMI response of a ring target in various levels of super-paramagnetic ground.*

5. Conclusions

The modeling results give insight into how magnetic soil couples with the response of a target. The effects of the super-paramagnetic ground adversely affect the response of an EMI sensor diminishing its ability to find visually obscured objects. Future work aims to incorporate the electric circuits' physics to model transient effects and modeling ground penetrating radar using the RF module.

6. References

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