MODELING THE MEASURED EM INDUCTION RESPONSE OF TARGETS AS A SUM OF DIPOLE TERMS EACH WITH A DISCRETE RELAXATION FREQUENCY

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INTRODUCTION

Simple electromagnetic induction (EMI) sensors are capable of detecting most landmines; however, they will also detect every buried metal object such as bottle tops, nails, shrapnel, bullets, etc. This results in an unacceptable false alarm rate. This is even more problematic for the detection of low-metal anti-personnel landmines as they are extremely difficult to distinguish from clutter using a simple EMI sensor. However, advanced EMI sensors that use a broad range of frequencies or a broad range of measurement times along with advanced signal processing have been shown to be capable of discriminating between buried landmines and many types of buried metal clutter [1-6]. The broadband responses of many targets and are relatively invariant to burial depth; however, the responses of some objects vary when they are tilted at odd angles, which could cause missed detections. To aid in the development of the EMI sensors and associated detection algorithms, a testing facility and inversion technique have been developed to characterize the response of typical targets and clutter objects with respect to location, orientation, and frequency. The data from these measurements will be used to study the response of the targets and develop models that are valid for any orientation of the object. Similar measurements in the field would be very difficult to perform due to the difficulty of accurately placing and rotating the target. It is difficult to analytically or numerically predict the response of many of these objects with accuracy due to uncertainties in the material parameters and geometry of the metal components in the objects. However, most objects can be modeled as simple sets of magnetic dipoles with discrete relaxation frequencies. It is envisioned that the models derived in this work will be utilized to reduce false alarm rates and increase the probability of detection for EMI sensors through improvements in both the hardware and the processing algorithms used to detect and discriminate buried targets.

MODEL

When a conductive target is placed in a time-varying magnetic field, electric currents are induced on the target. If the target is electrically small, the electric currents can be expressed in terms of the equivalent magnetic dipole moment, m. The dipole moment can be calculated from the magnetic polarizability, **M**, when the exciting field H_T

is relatively constant over the extent of the object: $\mathrm{m} = \mathbf{M}\mathrm{H}_\mathrm{T}$. A target will often have multiple relaxations and will have a corresponding tensor for each relaxation that contains the orientation/symmetry information for the relaxation. The magnetization for such a target can be written as a sum over the relaxations [4]:

$$\mathbf{M}(\omega) = M_0\mathbf{T}_0 - \sum_k M_\mathrm{k}\left(\frac{j\omega/\zeta_k}{1+j\omega/\zeta_k}\right)\mathbf{T}_k \tag{1}$$

where M_k is a real constant, ζ_k is the relaxation frequency, and $\mathbf{T}_k$ is a real, symmetric, second rank tensor. The form of the tensor $\mathbf{T}_k$ depends on the symmetry of the currents for the relaxation k. As an example, a target that consists of three orthogonal loops of copper wire, as in Fig. 1b, was constructed with the parameters shown in Table I. The magnetization of this target can be shown to be

$$\mathbf{M}(\omega) = -M_x\left(\frac{j\omega/\zeta_x}{1+j\omega/\zeta_x}\right)\begin{bmatrix}1&0&0\\0&0&0\\0&0&0\end{bmatrix} - M_y\left(\frac{j\omega/\zeta_y}{1+j\omega/\zeta_y}\right)\begin{bmatrix}0&0&0\\0&1&0\\0&0&0\end{bmatrix} - M_z\left(\frac{j\omega/\zeta_z}{1+j\omega/\zeta_z}\right)\begin{bmatrix}0&0&0\\0&0&0\\0&0&1\end{bmatrix}$$

where $M_\mathrm{k} = \mu_o A_k^2 / L_k$, $\zeta_k = 2\pi f_{rk}$, A_k are the areas of the loops and, L_k are the self inductances of the loops with $k = x, y, z$.

Table I. Parameters for the three-loop target.

Loop Parmeters			Theoretical Model Parameters		Measured Model Parameters	
Orientation	Diameter (cm)	Wire Gauge (AWG)	Magnetization M_k *10^6 (m^3)	Relaxation Freq. (kHz)	Magnetization M_k *10^6 (m^3)	Relaxation Freq. (kHz)
x	5	36	24.5	172	24.4	175
y	4	30	14.7	50.2	14.7	52.6
z	3	22	8.0	10.1	7.6	10.5

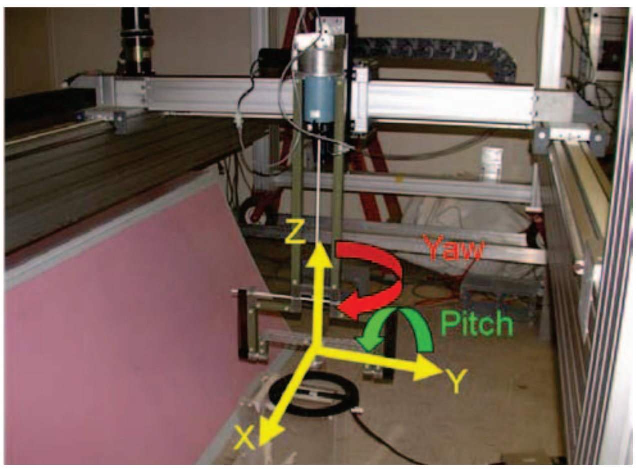
MEASUREMENT SYSTEM AND RESULTS

A laboratory positioner was developed with three automated translational stages (*x*, *y*, and *z*), two automated rotational stages (yaw and pitch), and one manually-adjusted rotational stage (roll, not labeled) as indicated in Fig. 1 [7]. An EMI sensor array [8] is shown in Fig. 1b with the three loop target. This system is used to measure the response of targets in a three-dimensional region as a function of angular orientation. Other typical targets include shell casings, ball bearings, coplanar wire coils, and landmines.

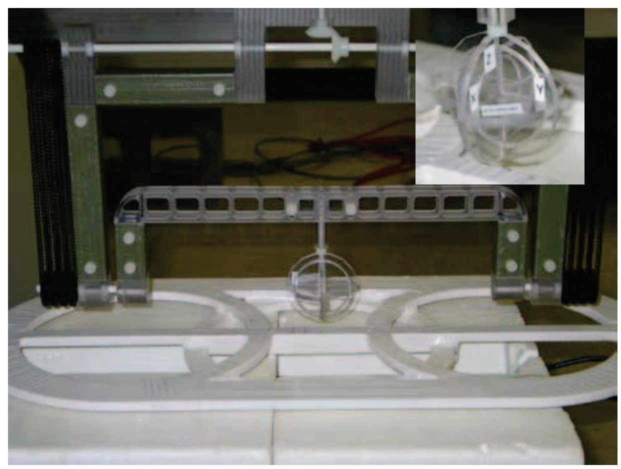
The system was used to measure the response of the three-loop target as a function of x, y, z, pitch, and yaw. This data were then filtered using the down-track filter that is normally used with this system [7]. Finally, using a model for the EMI system, an inversion technique that is similar to that in [8] is developed and used to calculate the best-fit parameters of eqn. 1 to the measured data. In this fitting procedure, the target is restricted to having two-fold symmetry which forces $\mathbf{T}_k$ to be diagonal:

$$\mathbf{T}_k = \begin{bmatrix} T_x & 0 & 0 \\ 0 & T_y & 0 \\ 0 & 0 & T_z \end{bmatrix}. \quad (3)$$

The theoretical and estimated model parameters shown in Table I and in Fig. 2 demonstrate good agreement. The theoretical results have a single component for each relaxation frequency, but the estimated results have multiple components for each relaxation frequency. The correct component agrees with the theory in both magnitude and frequency; the additional components are much smaller and are probably due to measurement errors. More description of the techniques and additional examples will be provided in the full paper.



a)



b)

Fig. 1. Experimental measurement facility for EMI target characterization: a) Automated translational (x, y, and z) and rotational (yaw about z and pitch about y) axes labeled, manual rotational axis not labeled, b) Three-loop target (in inset photograph) shown above EMI sensor array.

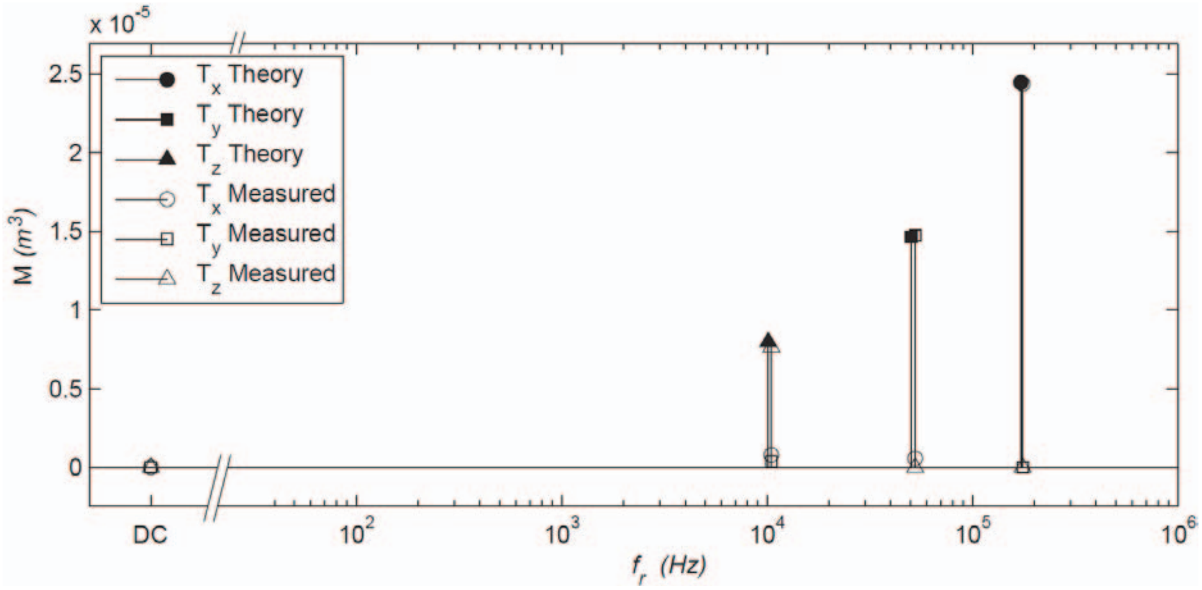


Fig. 2. Estimated and theoretical model parameters for the three-loop target as a function of relaxation frequency.

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