ESTIMATION AND APPLICATION OF DISCRETE SPECTRUM OF RELAXATIONS FOR ELECTROMAGNETIC INDUCTION RESPONSES

Mu-Hsin Wei, Waymond R. Scott, Jr., and James H. McClellan

Georgia Institute of Technology
School of Electrical and Computer Engineering
777 Atlantic Drive NW, Atlanta, GA 30332-0250

1. INTRODUCTION

The landmine crisis remains today as mines continue to maim or kill civilians everyday worldwide. The International Campaign to Ban Landmines reported that in the year of 2007, mines and explosive remnants of war caused 5426 casualties worldwide, of which 67% are civilians [1]. Much effort and research have been invested in remediating landmines with one of the primary tasks being the detection of the mine itself. Recent research has shown the use of broadband electromagnetic induction (EMI) sensors together with advanced signal processing are capable of discriminating between certain types of buried targets [2, 3], and it is within this framework the presented work is developed.

The EMI response of a metallic target can be accurately modeled by a sum of real exponentials [4]. It is difficult, however, in practice to obtain the model parameters from measurements. An EMI target response $H(\omega)$ can be expressed in the frequency domain as:

$$H(\omega) = c_0 + \sum_{k=1}^{K} \frac{c_k}{1 + j\omega/\zeta_k} \tag{1}$$

where c_0 is the shift, K the model order, c_k the real spectral amplitudes, and ζ_k the relaxation frequencies. The unknown model order K is one of the challenges in estimating the model parameters given the frequency response $H(\omega)$. For most existing estimation methods, a good guess of the model order is required for the fitting process to converge, otherwise it fails [5]. Prior knowledge of the model order, however, is difficult, if not impossible to obtain. The other challenge in estimating the model parameters in (1) is the highly correlated summands and the nonlinear relation between c_k and ζ_k. For this reason, existing methods often suffer from (a) sub-optimal solutions that are far from the truth and (b) complex parameters that do not have physical meaning [6].

2. A CONSTRAINED LINEAR ESTIMATION METHOD

We propose a robust estimation method for the model parameters that requires no prior knowledge of the model order, returns only real parameters, and is mostly free from the nonlinear problems that most existing methods face. The estimation problem is first linearized by enumerating a large set of possible relaxation frequencies $\tilde{\zeta}_m$, and express $H(\omega)$ as in (1) but with the enumerated $\tilde{\zeta}_m$ and corresponding spectral amplitudes $\tilde{c}_m$, the unknowns. Then minimize the squared error with respect to $\tilde{c}_m$ with a nonnegative constraint imposed. The true relaxation frequencies can then be inferred from the nonzero estimated $\tilde{c}_m$. The nonnegative constraint on the spectral amplitudes which is essential to keep the solution space small, derives from the observation that the real part of the frequency response decreases as the frequency increases, and the imaginary part is negative.

The proposed method performs well on synthetic, laboratory, and field EMI data. The synthetic data test the accuracy of the returned estimates; laboratory data test the physical validity of the estimates; and field data put the proposed method to practical use and is found to be quite robust. Figure 1 shows the ζ_k and c_k of a synthesized frequency response, and also their estimates, which are very close to the truth. Figure 2 shows the robustness and consistency of the estimated ζ_k and c_k for medium-metal content antipersonnel mines of the same type from field data. The results are for eight different mines buried at different locations and depths.

Since ζ_k and c_k concisely characterize a $H(\omega)$, we compactly and conveniently refer to the set of ζ_k and c_k the Discrete Spectrum of Relaxation Frequencies (DSRF). The DSRF is simply related to the "Distribution of Relaxation Times" (DRT) in polymer science which also uses models that are sums of exponentials [7].

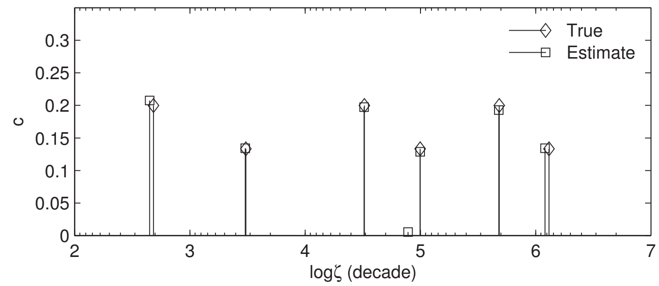

Fig. 1. Estimation of ζ_k and c_k of a frequency response of model order six.

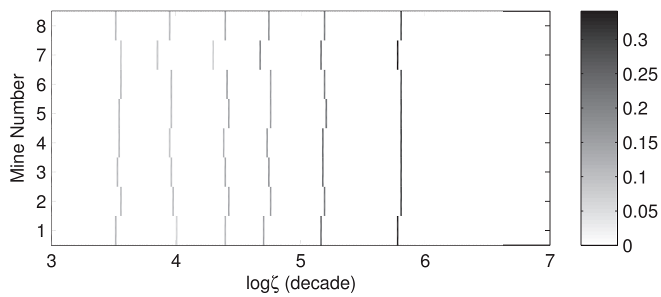

Fig. 2. Estimated ζ_k and c_k of low-metal content antipersonnel mines of the same type. The spectral amplitude is represented by the intensity: darker the color, larger the amplitude.

The relaxation frequencies of a target are intrinsic and orientation-invariant unlike the spectral amplitudes which are orientation dependent. Using both quantities, i.e., the DSRF, the characteristics and properties of a target can be inferred implicitly. We therefore propose a simple yet practical classification algorithm based on the DSRF to demonstrate the potential use of the DSRF in target discrimination.

3. REFERENCES

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