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MEASUREMENT OF COMPLEX NATURAL RESONANCES OF TARGETS IN FREE SPACE AND LOSSY MEDIA

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Abstract–The scattered fields of a number of targets in free space are measured. Their complex natural resonances are extracted from the late time responses, using the generalized pencil-of-function method. The complex natural resonances, as the targets are immersed in a lossy medium, are investigated using Baum's transform. The results of the complex natural resonances for various targets are expected to be utilized for target identification.

1. INTRODUCTION

Ground penetrating radar (GPR) using electromagnetic waves to detect underground objects, such as mines or unexploded ordnance (UXO), has attracted intensive investigations [1, 2]. Several theoretical methods are used to analyze the scattering behavior of targets buried in a lossy ground, such as finite difference time domain (FDTD) and the method of moments (MoM) combined with Fourier transform. The resonances of a number of conducting and dielectric objects in lossy media have been analyzed using numerical methods [3–5]. However, most practical targets, due to their complex shapes and constitutive material, have to be measured. The measurements for the scattering of buried objects using a GPR have been carried out by some research groups and the complex natural resonance (CNR) signatures were extracted and discussed from the measured data, for example [2, 6, 7]. In this paper, we measure the scattering behavior of a number of targets in free space and then extract their CNRs from the late time domain responses, using the generalized pencil-of-function (GPOF) method [8]. Baum's transform, which relates the CNRs of a conducting object in a lossy homogeneous medium to those in free space, is finally applied to investigate the CNR of the targets when the targets are immersed in a lossy medium [9]. We then compare natural resonances measured in a lossy medium, using a GPR, with the resonances estimated using Baum's method. The results of CNR for various targets are expected to be utilized for target identification. This measurement technique provides an alternative and simple way to investigate the CNR of complex objects in free space and lossy environments.

2. EXPERIMENTAL PROCEDURE AND DATA PROCESSING

The scattering of objects is measured in an anechoic chamber (in free space). The HP8530 microwave receiver (8510C software) is used with HP83651A synthesized sweeper and HP8517A S-parameter test set. Two TEM cepstra horns are used as transmitting and receiving antennas. A low noise amplifier, with gain 10 dB, noise figure 5 dB and bandwidth 20 MHz to 7 GHz, is used between the receiving antenna and microwave receiver to improve the signal to noise ratio. The one path 2-port model for RCS calibration is used to calibrate the network analyzer to display S_{21} [10]. An open-short-load reflection calibration is performed at the end of the cable that connects the transmitting antenna before making the isolation and transmission measurements to avoid disturbing the anechoic chamber. Then we make all the transmission measurements in the 2-port calibration procedure with the reference target (a 100 mm diameter, hemispherical-ended aluminum cylinder, as shown in Fig. 1(a)) in place. We confirmed the validating of measurement by checking the response of a 5 cm-diameter sphere. Finally, all isolation measurements are made of the room with the reference target removed.

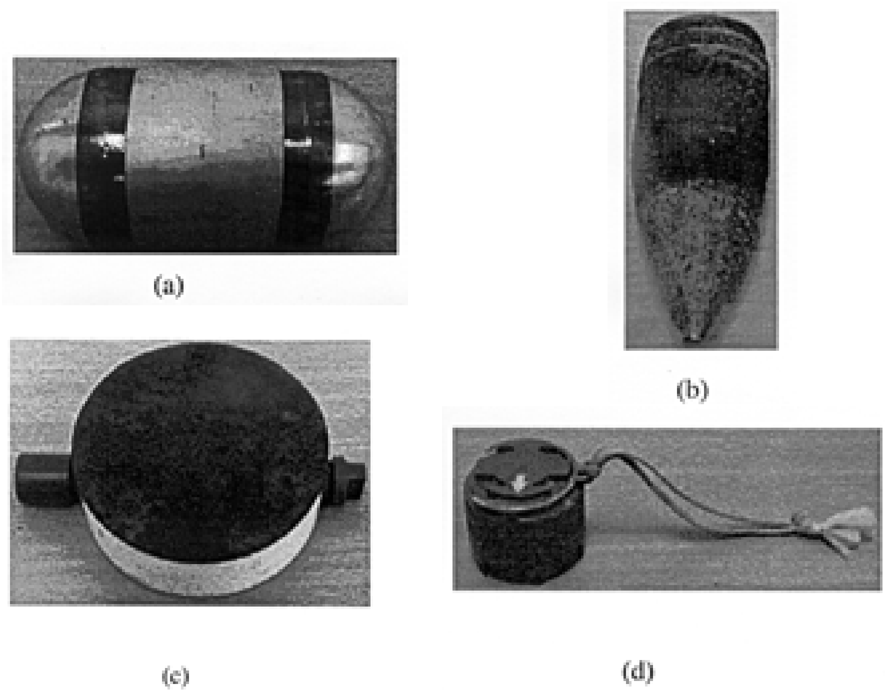

Figure 1. Photograph of targets (a) reference target (b) projectile (c) PMN surrogate (d) M14 surrogate.

After 201 points of S_{21} in the frequency range of 800 MHz to 5 GHz are recorded for the target, the time-domain response is obtained by the inverse FFT. The gating feature is used to further reduce the effects of the background reflections. A bandpass shaped time filter is used to selectively view the effects of individual portions of the time domain response. In converting back to the frequency domain by FFT, only the effects of the reflection inside the gate are viewed and the effects of the reflections outside the gate are removed. The result is a very smooth frequency domain response that very closely follows the shape of the ungated response but has significantly less clutter.

The GPOF method is used to extract the poles and residues from the windowed data in the late time response. The poles and residues are representative of the late time response and can be utilized to reconstruct it by

$$f((n-1)\Delta t) = \sum_{m=1}^{N} c_m e^{s_m (n-1)\Delta t}, \tag{1}$$

where c_m are the residues and $s_m = \sigma_m + j\omega_m$ are the poles, here σ_m are the damping factors and ω_m are the resonant frequencies [2]. The relationship between the CNR of a conductive object in a lossy homogeneous environment and those of the same object in free space is

$$s_m^h = -\frac{\sigma}{2\varepsilon_0\varepsilon_r} + \sqrt{\left(\frac{\sigma}{2\varepsilon_0\varepsilon_r}\right)^2 + \frac{s_m^2}{\varepsilon_r}}, \tag{2}$$

where s_m^h is the corresponding poles in a medium with real permittivity ε_r and conductivity σ [9]. It should be noted that the analysis of the resonances of objects in a lossy medium are significant since the perturbance of resonances introduced by the interface of a lossy half-space is small even for relatively shallow buried objects [3]. Moreover, the perturbance, in fact, could not be measured using GPR because of the impact of clutter on the measured data [11].

The resonances for a dielectric sphere in a dielectric medium are separated into external and internal modes [4]. The external resonances are caused by the surface creeping wave and are only slightly dependent on the internal material. The internal resonances are related to internal bouncing waves which experience multiple reflections and are little affected by the surrounding environment. The external resonances have much larger damping factors than the internal resonances, thus internal resonances are more important in practice. If these conclusions are extended to an arbitrarily shaped dielectric object in a lossy dielectric medium, it is a reasonable assumption that the transform can be applied to the external resonances. Hence the transform is still a useful way to study the resonances of an immersed dielectric object where the external resonance is dominant. However, it is difficult to identify the internal or external resonances from the measured data of the scattered field and it is unlikely that the transform can be applied to the internal resonances of plastic land mines. This idea is confirmed by Baum's theory [11]. It was pointed out that the transform could be applied to external resonances, however, a different formula was given to the internal resonances, which depend upon not only the surrounding and target media but also mode and target shape.

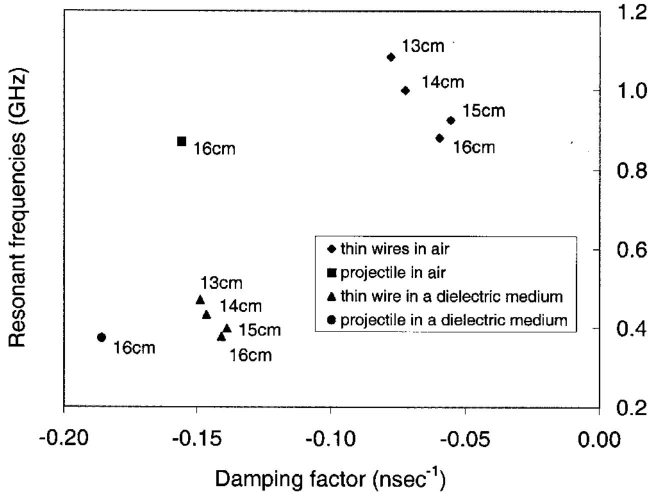

Figure 2. Poles of the thin wires of length 13 cm, 14 cm, 15 cm and 16 cm and a projectile of length 16 cm, in free space and in a lossy medium with $\varepsilon_r = 5$, $\sigma = 0.01$ s/m.

3. MEASURED RESULTS

The scattering of a number of targets are measured. Here we give some examples. To test the accuracy of the measurement, RCS of a conducting sphere with diameter of $5cm$ is measured and reasonable agreement with the exact Mie series solution is observed. The first example given here is the scattering of thin conducting wires with length $L = 13$ cm, 14 cm, 15 cm and 16 cm and ratio of length to radius $L/a = 200$, and a projectile with length $16cm$ as shown in Fig. 1(b). The targets are oriented parallel to the polarization of the antenna. Fig.2 shows the poles of the lowest mode. It is seen that the resonant frequency is close to (7% less than) the first order theoretical value $(f_{res} = c/2L)$, as expected [12]. It is interesting to note that the lowest pole of the projectile has a similar resonant frequency but has a much larger damping factor since the projectile has much larger radius hence has a lower Q-factor. It is interesting to look at the pole pattern when the wires or projectile are immersed in a lossy medium. Fig. 2 shows as well the poles of the thin wires of length 13 cm, 14 cm, 15 cm and 16 cm and the projectile of length 16 cm, in a lossy medium with $\varepsilon_r = 5$, $\sigma = 0.01$ s/m. It is seen that the pattern looks similar to the free space case. The second example investigates by measurement

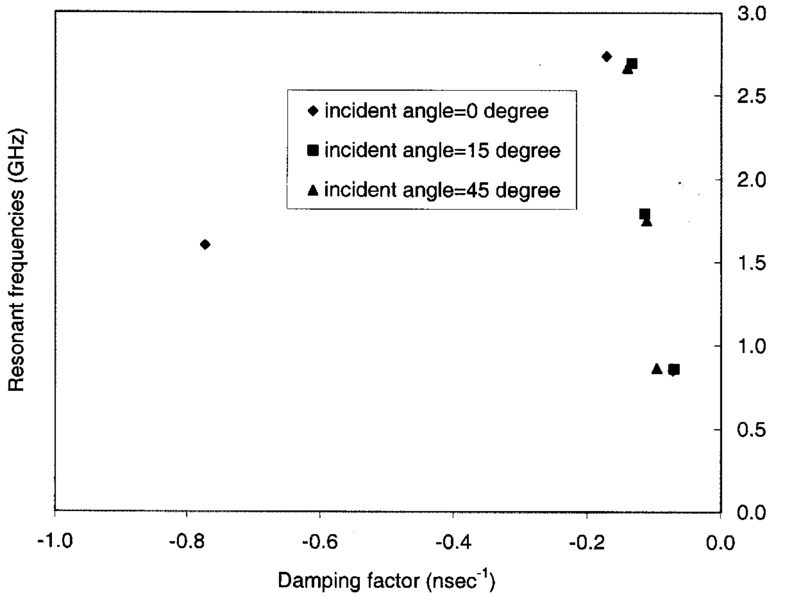

Figure 3. Poles of a wire (length $L = 16\,\text{cm}$), in free space, with different incident angles $0°$, $15°$, $45°$.

of the influence of incident angles on the resonances. Fig. 3 shows the poles of the wire of length 16 cm in free space illuminated by different incident angles $0°$, $15°$ and $45°$. It is observed that the resonant frequencies do not differ much hence demonstrating resonant frequencies are aspect independent by the measurement. It is also seen that the damping factor of the second resonance are very high because of the symmetry of the wire, as expected. The third example is a measurement of the scattering of two-identical parallel wires of length 12 cm coupled with each other in air. Fig. 4 shows the poles (of the coupling between two wires) variation with the separation distance between the two objects in air. The pole of a thin wire with the same length is also shown in the figure for comparison. It is clearly demonstrated that the spiral pattern of the lowest-mode pole exists for the two coupling identical wires as theoretically analyzed in [13]. Fig. 5 shows the poles of the two wires when they are immersed in lossy media with $\varepsilon_r = 5$ and $\sigma = 0.0\,\text{s/m}$ and $0.01\,\text{s/m}$. It is seen as expected that the resonant frequencies decrease and damping factors increase when the dielectric constant and conductivity increase, respectively.

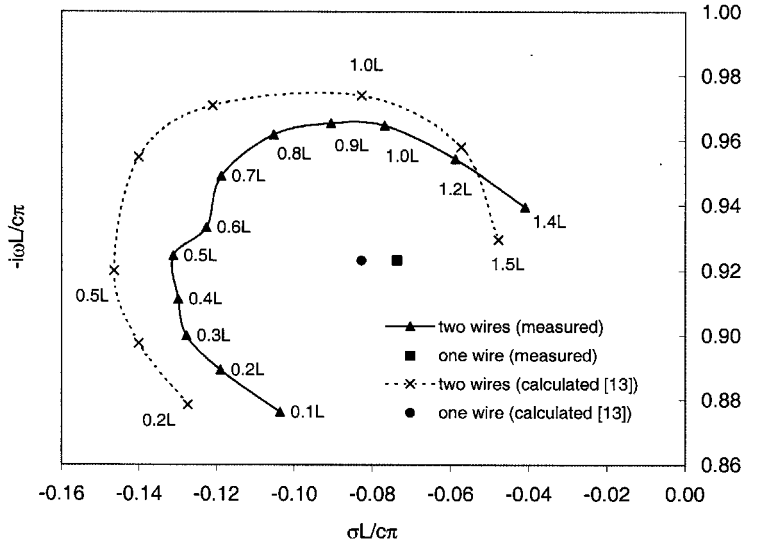

Figure 4. Poles of a pair of parallel wires (length $L = 12\,\mathrm{cm}$) in free space at different spacings.

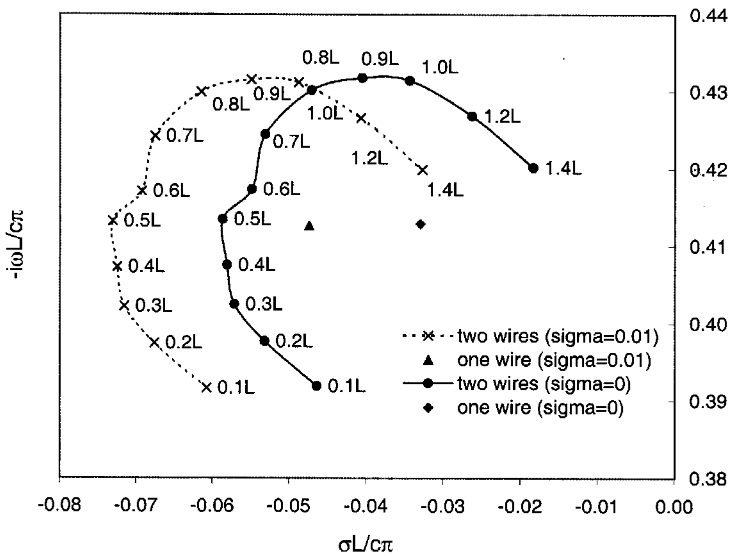

Figure 5. Poles of a pair of parallel wires (length $L = 12cm$), measured in free space and transformed to lossy dielectric media ($\varepsilon = 5$ and $\sigma = 0.0\,\mathrm{s/m}$ or $0.01\,\mathrm{s/m}$), at different spacings.

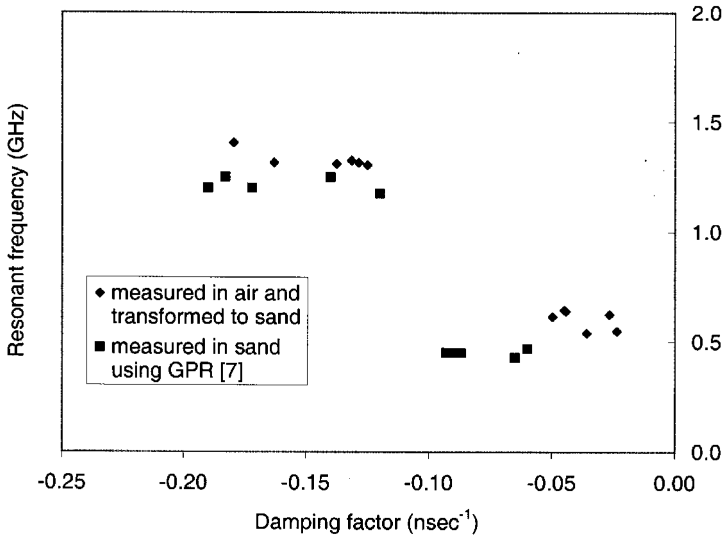

Figure 6. Poles of an anti-personnel landmine (surrogate PMN), at different aspect angles, in a lossy dielectric medium with $\varepsilon_r = 4$ and $\sigma = 0.01\,\text{s/m}$, compared with measured data using a GPR taken from [7].

However, it is also observed that the spiral pattern still holds for two coupling wires immersed in a homogeneous lossy medium. The last example is the scattering measurement of an anti-personnel landmine, a surrogate PMN as shown in Fig. 1(c). Fig. 6 shows the two lowest poles of the surrogate PMN measured in free space and transformed to dry sand with $\varepsilon_r = 4$ and $\sigma = 0.01\,\text{s/m}$. Different data of the poles are collected when changing the objects orientation. Compared with the poles measured by a GPR where the same type of landmine is buried at depth of 0.5 cm under dry sand presented in [7], it is seen that the poles measured by this technique have similar patterns to the poles measured using a GPR. It should be noted that here we estimate the electrical parameters of dry sand since the paper [7] did not give the measured values. For small plastic anti-personal mines such as the M14 as shown in Fig. 1(d), however, it is found that the electromagnetic response is much weaker than that from the surrogate PMN and the signal received is almost merged in background clutter. However, we can still find evidence of the resonances from the scattering spectrum, although the resonances are quite difficult to be accurately extracted from the received signal.

4. CONLCUSION

The complex natural resonances of targets in free space and lossy environments are extracted, and inferred using Baum's transform, from measured data of scattered fields in free space. A number of examples are presented to show the accuracy and efficiency of this measurement technique. It suggests a simple way to analyze the complex natural resonances of complex objects and their variation with their surrounding environments.

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