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On the Polarization Response Using Resonances for Target Recognition

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Abstract — In most studies concerning resonance based target recognition, targets are usually excited and measured using a linear polarized basis and at the same time ignoring the cross polarization component. In this paper, the possibility of using circular polarization in this context is investigated. Numerical results of some simple wire targets demonstrate that it would be easier to fully excite all of the important resonances using a circular polarization basis with due consideration of the co- and cross-polarized directions.

Index Terms **—Transient Electromagnetic Scattering, Resonance-based Target Recognition, Polarization.**

I. INTRODUCTION

Over the years target recognition based on transient electromagnetic scattering has been of significant interest. In the mid 1970s, Baum introduced the Singularity Expansion Method (SEM) [1]-[2] that considers the application of circuital concepts such as the impulse response and the transfer function to electromagnetic scattering phenomena. According to the SEM, the late time portion of a scattered transient electromagnetic signature can be modeled as a sum of damped exponentials. Such damped exponentials correspond to the Natural Resonant Frequencies (NRF) of the target. Theoretically, these NRFs are purely dependent on the physical properties of the target such as its geometry and its dielectric properties and are independent of both incident aspect and polarization states [1]-[3]. This aspect and polarization independence of the NRFs allows the usage of SEM as an excellent candidate for target classification.

Recent efforts have started looking into the prospects of using NRF polarization properties as an additional source of information for radar target identification. Shuley and Longstaff [3] considered the polarization dependency of the NRFs and found that the residues of the extracted NRFs vary as the incident polarization angle varies (They only considered linear polarization states). Lui and Shuley [4] also looked into different ways of handling the various target signatures obtained from various linear polarization states.

Probing further on the results of [3], if we simply excite the object at a particular linear polarization state at a particular aspect, it is highly possible that only a certain number of resonant modes can be excited with some modes being either weakly excited or not even excited at all. Consider an automated target recognition (ATR) scenario of a number of targets with overall similar physical attributes but with different substructures, it is important that these ‘substructure’ resonance [5]-[6] are properly excited so that the targets can be easily discriminated. Of course, one can argue that we can also choose an excitation aspect such that all the NRFs and substructure resonances can be properly excited. However, instead of following this trivial case, in this paper, we are considering the situation of different excitation polarization states at a single aspect.

The paper is outlined as follows. A brief review of the SEM is given in the next section followed by some updates on polarization issues in the context of resonance based target recognition. Numerical examples of some wire objects with different linear and circular polarization states will be given in section IV and conclusions will be reached towards the end of the paper.

II. THE SINGULARITY EXPANSION METHOD

Upon excitation of the target in free space using a short electromagnetic pulse, the late time of the target signature can be expressed as [1]-[2]

$$r(t) = \sum_{n=1}^{N} a_n e^{\sigma_n t} \cos(\omega_n t + \phi_n), \qquad t > T_l \qquad (1)$$

where a_n and $ø_n$ are the aspect dependent residues and phase of the n^{th} mode respectively and T_l is the onset of the late time period. It is assumed that only N modes are excited under band-limited short-pulse excitation. The NRFs are given by $s_n = \sigma_n \pm j\omega_n$, where σ_n and ω_n are the damping coefficients and resonant frequencies respectively. These NRFs correspond purely to the physical properties of the target’s geometry, dielectric properties and loss mechanisms and are theoretically aspect independent. They can therefore be used as a feature set for target recognition.

III. POLARIZATION IN THE CONTEXT OF COHERENT SCATTERING

To our knowledge, most studies in the context of resonance based target recognition are concerned with linear polarization excitation at a particular aspect. Usually only the co-polarized component is considered. The idea

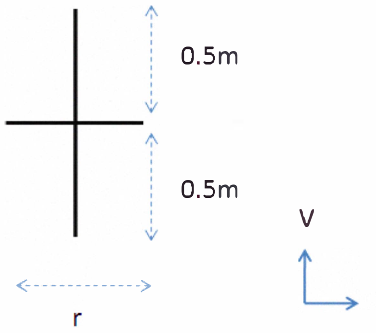

Fig. 1. Wire targets and corresponding excitation polarization references. Target 1: $r=0.3m$, Target 2: $r=0.2m$ and Target 3: $r=0.4m$

$l=\frac{\lambda}{2}$	f_R	$\frac{\omega_n}{c}=\frac{2\pi f_R}{c}$	Corresponds to
1m	150MHz	3.14	Main body
0.4m	375MHz	7.85	Target 3
0.33m	455MHz	9.52	Main body
0.3m	500MHz	10.47	Target 1
0.2m	750MHz	15.70	Target 2
0.15m	1GHz	20.94	Main body
0.1m	1.5GHz	31.42	Target 1

Table 1. Lengths of wire segments and their corresponding half wavelength resonant frequencies

of using different polarization states to excite or measure the target signature has not been well exploited.

Consider an orthogonal linear polarization basis with horizontal and vertical components, (H,V). The relationship between the scattered electric field components $\vec{E}_s(H,V)$ and the incident electric field components $\vec{E}_i(H,V)$ from a radar target in the frequency domain is given by [7]

$$\vec{E}_s(H,V)=\begin{bmatrix}S_{HH} & S_{HV}\\ S_{VH} & S_{VV}\end{bmatrix}\vec{E}_i(H,V) \qquad (3)$$

where $\vec{E}(H,V)=\left[E_He^{j\delta H} \quad E_Ve^{j\delta V}\right]^T$, $E_He^{j\delta H}$ and $E_Ve^{j\delta V}$ are the horizontal and vertical electric field components. $[S(H,V)]=\begin{bmatrix}S_{HH} & S_{HV}\\ S_{VH} & S_{VV}\end{bmatrix}$ is the scattering matrix. The terms S_{HH}, S_{HV}, S_{VH} and S_{VV} correspond to the ratios between the incident and scattered electric field components. For instance, $S_{HV}={S_H^s}/{S_V^i}$ corresponds to the ratio between scattered electric field in the horizontal polarization over the incident electric field in the vertical polarization. Given the scattering matrix in a linear HV basis for the monostatic case, it can easily be converted to a general elliptical basis, using the unitary transformation given by

$$[S(A,B)]=\begin{bmatrix}S_{AA} & S_{AB}\\ S_{BA} & S_{BB}\end{bmatrix}=[U]^T[S(H,V)][U], \qquad (4)$$

where $[U]=\frac{1}{\sqrt{1+\rho\rho^*}}\begin{bmatrix}1 & j\rho^*\\ \rho & -j\end{bmatrix}$. The polarization ratio ρ is given by

$$\rho=\left|\frac{E_V}{E_H}\right|e^{j(\delta V-\delta H)}. \qquad (5)$$

For Left-Hand Circular (LHC) and Right-Hand Circular (RHC) polarizations, the polarization ratio are j and $-j$ respectively. Given $[S(H,V)]$ together with (4), the scattering matrix in circular polarization basis can be obtained:

$$[S(L,R)]=\begin{bmatrix}S_{LL} & S_{LR}\\ S_{RL} & S_{RR}\end{bmatrix}. \qquad (6)$$

Note that the above description concerns the scattering phenomena at a particular frequency in the frequency domain. In this paper, we concentrate on the scattering matrix in the UWB context. If we take an inverse Fourier Transform of the wideband frequency domain data, the scattering matrices in time domain can be written as

$$\left[S_{(H,V)}(t)\right]=\begin{bmatrix}S_{HH}(t) & S_{HV}(t)\\ S_{VH}(t) & S_{VV}(t)\end{bmatrix} \qquad (7a)$$

$$\left[S_{(L,R)}(t)\right]=\begin{bmatrix}S_{LL}(t) & S_{LR}(t)\\ S_{RL}(t) & S_{RR}(t)\end{bmatrix} \qquad (7b)$$

IV. NUMERICAL EXAMPLES

To investigate how the excitation and receiving polarization states affect the performance of resonance based target recognition, numerical examples of three wire targets with a vertical wire segment (main body) of 1m and a horizontal wire segment of $r=0.3m$, $0.2m$ and $0.4m$ respectively, shown in Fig. 1 are considered. The targets are excited with both vertical and horizontal polarization. The fundamental resonant frequency for a wire with length l can be approximated by

$$f_R=\frac{c}{(2\times l)} \qquad (8)$$

where $c=3\times10^8 m/s$. The resonant frequencies of different wires are listed in Table 1. This gives us some

Linear Polarization Basis			**Circular Polarization Basis**		
Target 1	**Target 2**	**Target 3**	**Target 1**	**Target 2**	**Target 3**
VV	**VV**	**VV**	**LR**	**LR**	**LR**
$-0.11 \pm j3.06$	$-0.11 \pm j3.06$	$-0.11 \pm j3.06$	$-0.11 \pm j3.06$	$-0.11 \pm j3.06$	$-0.11 \pm j3.06$
$-0.17 \pm j9.32$	$-0.17 \pm j9.32$	$-0.17 \pm j9.32$	$-0.18 \pm j9.32$	$-0.18 \pm j9.32$	$-0.18 \pm j9.32$
$-0.21 \pm j15.61$	$-0.21 \pm j15.61$	$-0.21 \pm j15.61$	$-0.23 \pm j15.61$	$-0.26 \pm j21.95$	$-0.22 \pm j15.61$
$-0.22 \pm j28.31$	$-0.22 \pm j28.31$	$-0.22 \pm j28.31$	$-0.26 \pm j22.01$	$-0.47 \pm j15.81$	$-0.30 \pm j7.63$
$-0.24 \pm j21.93$	$-0.24 \pm j21.93$	$-0.24 \pm j21.93$	$-0.39 \pm j10.17$	$-0.80 \pm j15.51$	$-0.71 \pm j22.62$
HH	**HH**	**HH**	**LL**	**LL**	**LL**
$-0.40 \pm j10.18$	$-0.02 \pm j15.02$	$-0.30 \pm j7.63$	$-0.11 \pm j3.06$	$-0.11 \pm j3.06$	$-0.11 \pm j3.06$
$-0.64 \pm j31.17$	$-0.63 \pm j15.26$	$-0.49 \pm j23.33$	$-0.17 \pm j9.32$	$-0.17 \pm j9.32$	$-0.17 \pm j9.32$
		$-0.59 \pm j39.21$	$-0.21 \pm j15.61$	$-0.24 \pm j15.60$	$-0.23 \pm j15.62$
			$-0.27 \pm j21.94$	$-0.24 \pm j21.96$	$-0.30 \pm j7.63$
			$-0.40 \pm j10.18$	$-0.62 \pm j15.30$	$-0.33 \pm j22.64$

Table 2. Extracted NRFs from $S_{VV}(t)$, $S_{HH}(t)$, $S_{LL}(t)$ and $S_{LR}(t)$. The NRFs are all normalized by the factor of c, i.e. $\frac{s_n}{c} = \frac{\sigma_n \pm j\omega_n}{c}$.

idea of what the extracted NRFs should be. The scattered fields of both co- and cross-polarization are measured at the monostatic direction such that the four components in the scattering matrix S_{HH}, S_{HV}, S_{VH} and S_{VV} are obtained. The electromagnetic scattering problems are solved using commercial moment method solver FEKO [8] in frequency domain from 3.9MHz to 2GHz with 512 equally spaced samples. Thin wire approximation is used here with the radius of $10\mu m$. The frequency samples are first windowed via a Gaussian window [9] and inverse Fourier transformed to the time domain. Late time samples from 12ns to 137ns are imported to the Matrix Pencil Method [10] for NRF extractions. The extracted NRFs from $S_{VV}(t)$ and $S_{HH}(t)$ are listed in Table 2.

It is found that for the extracted NRFs from $S_{VV}(t)$ for the three targets are identical (to 2 decimal places). There are some minor differences (4th decimal place) which are not of practical significance. For $S_{VV}(t)$, only the 1m wire segment of the 3 targets are well excited and the short wire segments of 0.2 to 0.4m for each target, which are perpendicular to the excitation. Under vertical excitation, the single horizontal wire under is weakly or even not excited. For the case of $S_{HH}(t)$, however, the short wire segment is well excited (but not the 1m wire segment) and thus the extracted NRFs for the three targets are totally different. Compared with the estimated resonant frequencies in Table 1, it can be seen that the resonance of 1m, 0.33m and 0.15m corresponds to the fundamental and higher order resonance of the 1m main body of the three targets and the resonance of 0.4m, 0.3m, 0.2m and 0.1m corresponds to the fundamental and 2nd order resonance of the horizontal wire segment of the targets.

Next, the scattering matrix in the circular polarization basis in time domain is computed based on $[S(H,V)]$ in frequency domain, (4) and (5), followed by an inverse Fourier Transform of the wideband frequency domain data. NRFs are then extracted from $S_{LL}(t)$ and $S_{LR}(t)$. Under the mono-static configuration, $S_{LL}(t) = S_{RR}(t)$ and $S_{LR}(t) = S_{RL}(t)$ and thus we only need to consider $S_{LL}(t)$ and $S_{LR}(t)$. The results are shown in Table 2. The NRFs at $\omega_n/c \approx$ 3.06, 9.32,15.60 and 22, which correspond to the resonant frequencies from the 1m wire segment (as shown in Table 2 under VV and Table 1), are well excited in both $S_{LL}(t)$ $S_{LR}(t)$ for all the three targets. The NRFs of $\omega_n/c \approx$ 10.17, 15.30 and 22 for Target 1, 2 and 3 respectively, which corresponds to the short wire segment of each target (as shown in Table 2 under HH) . In particular, the two resonant modes at $\omega_n/c \approx$ 15.30 and 15.60 are accurately extracted for $S_{LL}(t)$ for Target 2.

The results here clearly show that if we excite and measure the co-polarized targets signature with vertical polarization state, the NRFs corresponding to the horizontal wire segment are poorly excited and thus a nearly identical set of NRFs is found. If one applies a target recognition scheme with these data, such as E-Pulse [2] or even a "Banded" E-Pulse [11], it is very unlikely that these techniques would be able to distinguish the targets. On the other hand, however, if one excites the target using circular polarization basis, the NRFs that correspond to both wire segments are well excited and the differences between the targets become much apparent even by just inspecting the extracted NRFs.

V. CONCLUSION

The possibility of using different polarization states in the context of resonance based target recognition is investigated. Numerical examples of three wire targets under linear and circular polarization states excitations and receptions are considered. It is found the use of circular polarization states can effectively excite the important NRFs that corresponds both the main body and the substructure of the targets, which would lead to more reliable results for target classification and recognition.

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