Application of DORT and Pulse Inversion to Detection and Selective Electromagnetic Focusing on Nonlinear Elements

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Abstract

In this work, we present the DORT (decomposition of the time-reversal operator) technique in combination with pulse inversion (PI) applied to detection and selective focusing on nonlinear targets. When nonlinear targets of interest are present in a field of linear scatterers, the harmonic responses from the nonlinear targets can be used as a distinguishing feature when applying DORT. Furthermore, PI suppresses fundamental and odd-order harmonics, retaining only the second harmonics originated from nonlinear targets of interest, thereby reducing clutter from unwanted linear scatterers and occasional natural nonlinear scatterers (rusty metals). Two-dimensional numerical simulations are presented for a basic demonstration of the proposed approach.

1. Introduction

Time-Reversal (TR) has proven to be an effective means of focusing electromagnetic energy and has been used in various applications [1, 2]. Based on the time-reversal invariance in the lossless wave equation, TR allows for the waves to backpropagate and focus back at the scatters (or sources) where the waves originated. When used with a multi-static system, TR improves wave focusing while giving the possibility to selectively focus to targets by means of DORT.

DORT (the decomposition of the time-reversal operator) is a TR-based processing technique that utilizes multistatic responses received with an array of antennas (transducers) to selectively focus waves (direct the beam) to any scatterer in an environment containing multiple scatterers. DORT implements eigenvalue decomposition (EVD) on the frequency domain multistatic data and their complex conjugate (frequency domain equivalent of time-reversal), generating a set of eigenvalues that represent the detected scatterers in the environment and the corresponding eigenvectors that represent paths to and from the scatterers. By feeding the array elements using the eigenvectors, selective focusing on targets of interest is achieved [3, 4]. DORT for selective focusing has led to many interesting applications in acoustics and electromagnetics. More recently, the use of DORT to detect nonlinear scatterers has been demonstrated for acoustic waves [5]. Harmonic responses from nonlinear scatterers can be used as a distinguishing feature from linear scatterers.

Nonlinear scatterers are also of interest in electromagnetics. In applications such as wireless power transfer, biomedical, and security, targets of interest typically consist of nonlinear elements (e.g., semiconductor junctions), and the ability to detect and selectively focus electromagnetic energy on targets of interest would be desirable. In [6], TR was applied to focus electromagnetic waves to a nonlinear element in a complex scattering environment using a single antenna. The work in [6], however, does not address selective focusing since standard TR was applied to the harmonic responses.

In this work, we demonstrate DORT applied to nonlinear electromagnetic scattering. In many realistic environments, nonlinear targets of interest are present in a field of linear scatterers, where the harmonic responses can be utilized as their distinguishing feature. Hence, by identifying the harmonics in the DORT eigenvalues, one can identify and selectively focus energy at the nonlinear target. Furthermore, we present the use of pulse inversion (PI) in combination with DORT (PI-DORT), which allows for suppression of scattering at fundamental and odd-order harmonics. The known advantage of PI is that it would resolve practical issues of any overlap between fundamental and harmonic responses, as well as any limited receiver dynamic range due to significantly weaker harmonic responses compared to those at fundamental band [6, 7]. For a multistatic system, there is an additional benefit of PI, that is, a complete removal of inter-element coupling. When targets are far enough away from the array (or transmit pulse is short enough), inter-element coupling can be removed via time-gating. However, when the target responses and inter-element coupling are not resolved, a background subtraction is typically performed to remove inter-element coupling. However, when PI is applied, inter-element coupling is inherently removed since PI suppresses any fundamental and odd-order harmonics. We demonstrate the application of PI-DORT using quasi-2D simulations carried out in CST Microwave Studio.

2. DORT Technique

Consider an N-element antenna array, where the time domain responses in all monostatic and bistatic combination are received. The DORT process begins with arranging the received time-domain data into an NxN multistatic matrix, \( K(t) \). Each column of \( K(t) \) represents the received responses when that column’s antenna is transmitting. The frequency domain data, \( K(\omega) \), is then obtained via Fourier
Transform. Time-reversal in the frequency domain is represented by the Hermitian transpose, $\mathbf{K}^\dagger(\omega)$. The time-reversal operator (TRO) is defined as $\mathbf{T}(\omega) = \mathbf{K}^\dagger(\omega) \mathbf{K}(\omega)$. DORT is then achieved by taking the singular value decomposition of the multistatic data matrices, that is, $\mathbf{K}(\omega) = \mathbf{U}(\omega) \mathbf{S}(\omega) \mathbf{V}^\dagger(\omega)$ and $\mathbf{K}^\dagger(\omega) = \mathbf{V}(\omega) \mathbf{S}(\omega) \mathbf{U}^\dagger(\omega)$. Thus, $\mathbf{T}(\omega) = \mathbf{V}(\omega) \mathbf{S}(\omega) \mathbf{V}^\dagger(\omega) = \mathbf{V}(\omega) \mathbf{S}(\omega) \mathbf{U}^\dagger(\omega)$, where $\mathbf{S}(\omega)$ represents the real-valued eigenvalues in a diagonal matrix with each eigenvalue corresponding to each detected (well resolved) scatterer in the environment. $\mathbf{V}(\omega)$ and $\mathbf{V}^\dagger(\omega)$ represent the eigenvectors describing forward and backward propagation to each target, respectively. The eigenvector matrix $\mathbf{V}(\omega)$ is used to generate a modulated Gaussian pulse centered at a given frequency $\omega_0$ with phase shift for each antenna equal to $\angle \mathbf{V}(\omega_0)$. The generated pulses transmitted from their respective antennas will result in a focus pulse at the selected target [3, 4].

3. Pulse Inversion

Pulse inversion is done by using two transmit pulses, namely $p(t)$ and $n(t)$, where $n(t) = -p(t)$. The scattered responses from a linear target due to these two pulses are also inverted, such that their linear combination is zero. For a passive nonlinear target, the harmonic generation can be expressed with a power series expansion as

$$
\begin{align*}
k^+(t) &= k_1 p(t) + k_2 p^2(t) + k_3 p^3(t) + \ldots \\
k^-(t) &= -k_1 p(t) + k_2 p^2(t) - k_3 p^3(t) + \ldots
\end{align*}
$$

The linear combination of $k^+(t)$ and $k^-(t)$ eliminates odd-order harmonics (and the fundamental response) and enhances the second order harmonics by a factor of 2, i.e.

$$k^+(t) + k^-(t) = 2k_2 x^2(t) + 2k_4 x^4(t) + \ldots
$$

This means that when both linear and nonlinear targets are present in the environment, pulse inversion would inherently suppress the fundamental responses. Since the linear scatterers do not generate any harmonics, pulse inversion allows for complete suppression of linear clutter. It is also useful for suppressing responses from unwanted natural nonlinear scatterers (e.g. rusty metals) that typically generate odd order harmonics [8].

4. Simulation Setup

To demonstrate the proposed approach, a quasi-2D electromagnetic model was generated in CST Microwave Studio. Two parallel PEC boundaries separated by 1 cm are placed in the $z$-axis. Since the separation between the PEC boundaries are much smaller than the wavelength, the model effectively represents a 2D space where the electric field is perpendicular to the $xy$ plane (TM$_0$) and radiate only in the $x$ and $y$ directions. A 12-element point source array was used with an element spacing of 7.5 cm (Fig. 1). The incident pulse used in the simulation was a modulated Gaussian pulse centered at 1.25 GHz with a bandwidth of 0.5GHz.

The first configuration includes two point targets as shown in Fig. 1a. One target is a linear scatterer represented by a short circuit (thin wire) connecting the top and bottom PEC boundaries and the other is a NL target represented by a diode. For this simulation, DORT was applied to two different sets of data. The first data is the multistatic response using a positive pulse $p(t)$ after background subtraction to remove inter-element coupling. The second set is the multistatic data after applying PI to eliminate fundamental (including inter-element coupling) and odd-order harmonics.

The second configuration consists of two nonlinear targets (also represented by diodes) as shown in Fig. 1b. DORT was applied after PI for selective focusing on each target using the second harmonic frequency.

5. Results

Fig. 2 shows the eigenvalues of TRO from the first configuration after background subtraction. Two significant eigenvalues are obtained, one representing the nonlinear scatterer and the other representing the linear scatterer. It is shown that only one of the eigenvalues, $\lambda_1$, has significant amplitudes in the harmonic bands. The eigenvectors associated with $\lambda_1$ and $\lambda_2$ at the fundamental center frequency (1.25 GHz) were used to generate modulated Gaussian pulses to feed the array. Two separate focusing simulations were run for $\lambda_1$ and $\lambda_2$ and the results are shown in Figs 3a and 3b, respectively. Even though $\lambda_1$ is the one with significant amplitude at harmonic bands, it waves generated based on $\lambda_1$ seem to focus at the linear target (Fig. 3a) and
the waves generated based on $\lambda_2$ focus at the nonlinear target, indicating that the eigenvalues were mixed up. One possible explanation is that, since EVD is done at each single frequency point without any information of EVD at other frequencies, the eigenvalues are obtained depending on the strongest scatterer at each frequency point. In other words, at the fundamental frequency band, the strongest scatterer is the linear scatter, and therefore it appears in the first eigenvalue. However at the harmonic frequencies, the nonlinear scatter is obviously the strongest scatterer, and thus it appears in the first eigenvalue.

Fig. 4 shows the eigenvalues of TRO from the first configuration after PI (PI-DORT). The fundamental and odd-order harmonics are minimized, making background subtraction unnecessary and eliminating the mix-up of the eigenvalues, since the only dominant eigenvalue is over the even-order harmonic bands. Fig. 5 show focusing at nonlinear target when the eigenvectors associated with $\lambda_1$ at the second harmonic frequency (2.5 GHz) were used to generate modulated Gaussian pulses to feed the array. The focusing occurs at the nonlinear target which is expected.

Fig 6. shows the eigenvalues of TRO for the second configuration (Fig. 1b) after applying PI-DORT. The fundamental and odd-order harmonics are also eliminated in this case, but two significant eigenvalues appear at even-harmonic bands since there are two nonlinear targets. Focusing simulations were run based on the eigenvector for $\lambda_1$ and $\lambda_2$, and the results are shown in Figs. 7a and 7b, respectively. As expected, each simulation shows wave focusing at each nonlinear element.
6. Conclusion

This paper presents DORT combined with pulse inversion (PI-DORT) as an effective method for detection and selective focusing of electromagnetic energy at nonlinear targets in an environment cluttered with linear scatters. Pulse inversion allows for the nonlinear targets to be more dominant and also mitigates inter-element coupling effects commonly seen in a multistatic system. A proof of concept is demonstrated with 2D numerical simulations, indicating that with further improvement and investigation, this PI-DORT approach could be instrumental in applications such as wireless power transfer, biomedical, and security, where detection and selective focusing of electromagnetic energy can be greatly utilized.

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8. References


