Radar Target Recognition Using Selective Resonance Excitation

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***Abstract*—Resonance-based radar target recognition is premised on the observation of natural resonant frequencies so that target discrimination and classification can occur. This implies the use of ultra-wideband (UWB) radar in order to excite a sufficiently wide range of target frequencies, however developing practical UWB radar systems is a significant challenge. Furthermore, due the relative weakness of the late-time resonant target response, it is often not possible to isolate the resonant frequencies under realistic noise conditions. To mitigate these limitations, this paper examines the feasibility of selective excitation of resonant frequencies using more traditional (narrow-to-medium band) excitation. Simulated target results are presented for which resonant frequencies are extracted, and the efficacy of selective excitation of these resonances is demonstrated.**

Keywords—radar target recognition; radar signature; ultra-wideband; complex natural resonances.

I. Introduction

It is a well-established theoretical result that the late-time resonant response of a target, generated by illumination with a wide bandwidth impulse, can be used to facilitate aspect-independent identification [1]. Since a reliable means of aspect-independent identification is a highly desirable goal, much work has been done to refine the method into a practical means of target identification [2, 3]. To date, however, the technique has generally failed to make an impact for target recognition applications [4] due to some critical limitations inherent in the method. These issues are outlined briefly below.

The principal complication with resonance-based radar detection is the vast difference in magnitude of the late-time complex natural resonances (CNRs) when compared to the initial backscattered signal. Apart from a few very simple, highly resonant (high Q) targets, the magnitude of the resonant components in the late-time period is typically 40-50 dB below the average signal power of the main (early-time) response [5]. This disparity means that for most practical scenarios involving distant targets the late-time response is not able to be separated from background noise.

A second limitation, linked to the first, is the fact that excitation of the late-time resonances requires that the target be illuminated by a broadband impulse in order that a sufficient number of resonances can be stimulated in the target. There are significant technical challenges associated with the generation and transmission of high power broadband impulses, particularly with regard to efficient broadband antenna design. In addition, regulatory authorities have placed strict limits on the frequency bands available for UWB propagation, restricting the development of radar systems for arbitrary target recognition (where the target resonant frequencies may well fall within restricted bands). Furthermore, even if a reasonably broadband signal is transmitted, the vast majority of the energy will be at frequencies that are not the resonant frequencies of the target, hence the ratio of available energy that can be reradiated by the target in the late-time compared to that in the early-time is very low [5].

In order to address these issues and still retain the benefits of the resonance-based recognition phenomenon, a different paradigm is required in terms of the radar design. Rather than attempting to illuminate all potential resonant target frequencies at the same time, a tuned narrowband signal is employed to selectively interrogate different frequencies (drawn from a library of CNRs for potential targets). Developing a tuneable narrowband radar system is much more feasible practically, and the fact that the signal is propagated over a small frequency range should dramatically improve the signal-to-noise ratio (SNR) when compared to a UWB radar. The theoretical feasibility of isolating individual target resonances has been demonstrated by others [6], so an examination of a narrowband approach to resonance-based target recognition is well motivated.

II. Method

A. Target Simulation and Resonant Frequency Isolation

To trial the concept of a narrowband system, we developed multiple simulations of simple target structures (wire-frame aeroplanes, Fig. 1) using the electromagnetic simulation package FEKO [7]. Three separate structures were created with specific variations in size and angle of fuselage and wings.

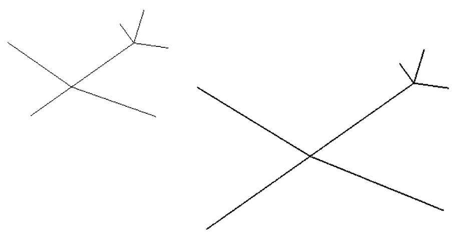

Fig. 1 Wireframe simulation models

The simulations were performed using the full-wave Method of Moments (MoM) analysis technique, with the target response extracted over a broad range of frequencies from 0.3 to 8 GHz. This synthesised broadband target response was then used to generate a time-domain impulse response for each target by means of the Inverse Fast Fourier Transform (IFFT). The dominant resonant frequencies for each target were then extracted; these poles, represented as poles in the complex s-plane (Fig. 2), are isolated from the late-time response of the target by means of the Matrix Pencil Method (MPM) [3].

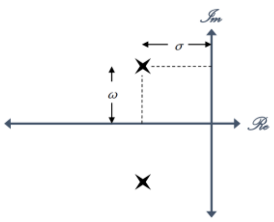

Fig. 2 Complex s-plane representation of resonant frequencies

Thus far, the analysis has mirrored the processed normally followed based on the assumption of a UWB source: the next step is to examine the process required to excite individual resonant frequencies when using a narrowband signal.

B. *Narrowband Excitation*

The simplest narrowband radars employ a continuous wave (CW) method to propagate the signal at a single frequency, typically for Doppler-based target velocity measurement [8]. For target ranging and discrimination, however, some form of modulation of the basic CW signal is required in order to isolate the time-range of the target. For resonance-based target recognition it is also essential that there be a windowed pulse in order that the late-time resonant response can be separated from the early-time scattering (in a CW scenario, the dominant and aspect-dependent early-time scattering would persist for the entire period of target illumination).

To allow the late-time response to develop, we consider a common radar signal modulation that is often used in a narrowband scenario: the coherent pulse train (Fig. 3). The Pulse Repetition Frequency (PRF) is a critical parameter for this scenario, as sufficient time is required between pulses in order that any late-time resonant response from the target can be isolated prior to the arrival of the following pulse.

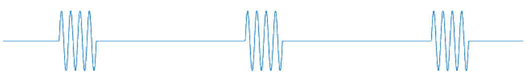

Fig. 3 Coherent Pulse Train

A complication immediately arises, however, when a CW narrowband signal is modulated by a pulse train: the frequency response is no longer the single-frequency spectrum of the true narrowband signal, hence the isolation of a single resonant frequency becomes more complicated. The spectral response of a coherent pulse train consists of a series of spikes or sidelobes centred on the main carrier frequency lobe and modulated by an envelope sinc function (Fig. 4).

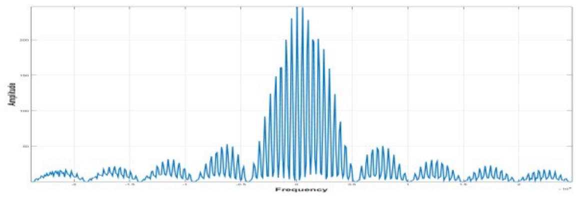

Fig. 4 Coherent Pulse Train Spectrum

The separation between the frequency lobes in the spectral response is equal to the pulse repetition frequency (PRF), with the frequency of the n^{th} pair of peaks from the central frequency given by:

$$\omega_n = \omega_c \pm n\omega_p$$

Here ω_c is the carrier frequency, and ω_p is the angular PRF ($\omega_p = 2\pi f_p$). The nulls of the sinc function envelope are determined by the pulse width, and occur at $\omega_c \pm 2\pi / \tau$, where τ is the pulse period (width).

To excite a particular resonant frequency for a given target in isolation using a pulse train will therefore require careful selection of the PRF and the pulse width to ensure that frequencies that correspond to other targets' resonances are not excited. Shaping the carrier envelope for the pulses (rather than using a simple square-wave) in order to alter the frequency response to damp the sidelobe peaks is another alternative.

C. *Waveform Agility*

A coherent pulse train is a fairly simple waveform, and more sophisticated approaches to the problem of CNR excitation are possible without resorting to an impulse-based (UWB) excitation of the target. Both pulse compression and stepped frequency systems allow a "medium-band" approach to cover a broad enough range of frequencies to stimulate one or more target poles [8]. If the radar system is "waveform agile", i.e., has the capability to dynamically adjust the transmitted waveform, then the transmit signal could be shaped as a time-reversed resonance waveform to maximise the excitation of a particular target mode (Fig. 5) within the band.

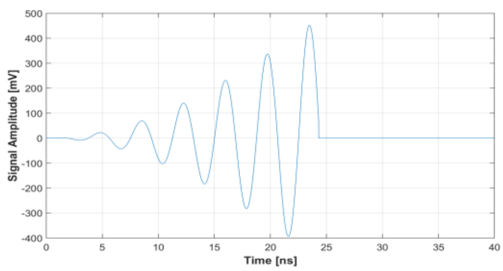

Fig. 5 Pulse envelope of a "time-reversed" mode shaped to a known CNR

III. Results

Initial results of the simulation for each of the three targets were generated in FEKO by means of a plane-wave excitation an incident angle of 45° to "nose on" for each wire plane.

A. *Time Domain Target Response*

The time domain impulse response for each target was generated using the multi-frequency FEKO simulation (Fig. 6).

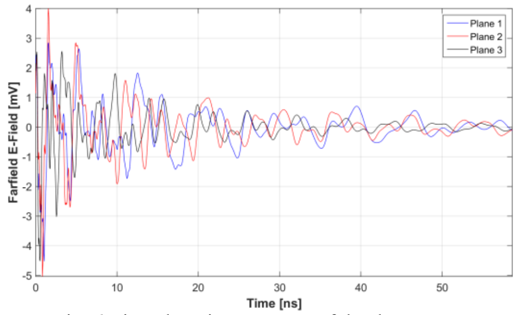

Fig. 6 Time domain responses of the three targets

B. *Target Resonant Frequencies*

The resonant frequencies for each target were then extracted from the time domain responses using the MPM. The target resonances are typically represented as poles in the complex s-plane (Fig. 2). However, due to the instability of the damping factor (σ), more reliable results for target recognition are obtained by using only the frequency (ω) of the resonant singularity (the imaginary axis in the complex s-plane), but using multiple samples to improve stability.

We have established elsewhere [9] that a target's CNR frequencies can be isolated, even in the presence of significant noise, first by means of repeated MPM extraction over multiple windows of a target response signal and then across multiple target responses. The resulting histogram of dominant frequencies (Fig. 7, showing the result for target 3) effectively raises the signal to noise (SNR) ratio of the late-time resonant response, allowing the natural resonant frequencies to be identified.

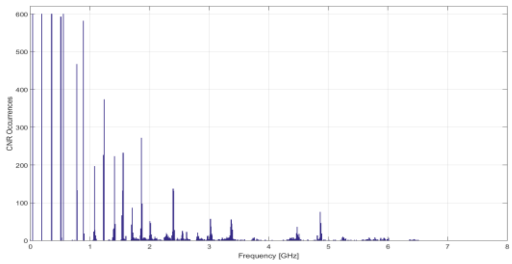

Fig. 7 Histogram of resonant frequencies for target 3

Using this technique, the CNRs for each of the three radar targets were extracted and tabulated to provide the necessary "library" of frequencies of interest to target with a modulated narrowband radar signal (Table I).

TABLE I FIRST 10 CNR FREQUENCIES, ALL TARGETS

CNR #	Plane 1 CNRs (GHz)	Plane 2 CNRs (GHz)	Plane 3 CNRs (GHz)
1	0.09221	0.10250	0.04098
2	0.12290	0.18440	0.19470
3	0.26640	0.30740	0.35860
4	0.34830	0.36880	0.51230
5	0.43030	0.53280	0.55320
6	0.54300	0.62500	0.77860
7	0.64550	0.66590	0.89130
8	0.72740	0.71720	1.07600
9	0.82990	0.85040	1.24000
10	1.02500	0.92210	1.41400

C. *Convolution with Narrowband Pulse Train*

Having extracted the resonant frequencies of the targets from a broadband analysis, it is now necessary to consider how these resonances could be observed when using a narrowband or similar excitation source. Three CNRs (one for each target) were selected as good candidates for discrimination based on there being reasonable separation from any nearby CNRs for the other two targets. Coherent pulse trains using these selected frequencies (highlighted in Table I) were then convolved with the target impulse responses. Note that all of the CNRs for a given target could be stimulated recursively using this method to provide a comprehensive target recognition scheme.

D. *Comparative Target Response to Narrowband Excitation*

Comparison of the late-time response of all three targets when excited by coherent pulse trains at each of these frequencies produces promising results. Note that for all of the results provided in these figures, only the late time response of each target is shown. For targets 1 (Fig. 8) and 3 (Fig. 10), the late time response to the excitation corresponding to that target's CNR is clearly of substantially greater magnitude than for the other two excitations. However, for target 2 the effect is less pronounced (Fig. 9): while the CNR frequency (0.625 GHz) does stimulate the largest magnitude late-time response, the response to the first frequency (0.2664 GHz) is less heavily damped, and persists longer into the late-time. This result would make target discrimination more difficult and increase the chances of a false identification.

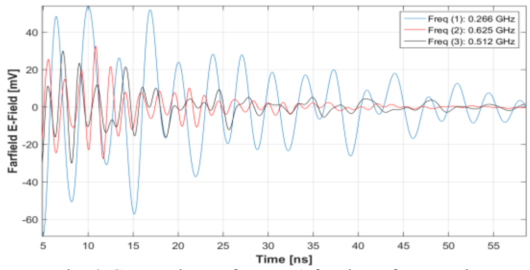

Fig. 8 Comparison of target 1 for three frequencies

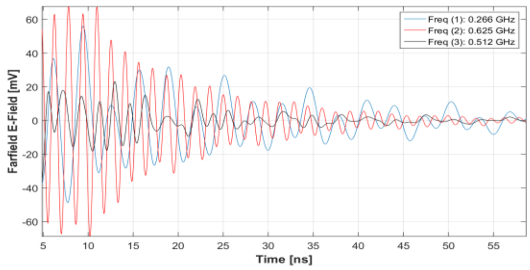

Fig. 9 Comparison of target 2 for three frequencies

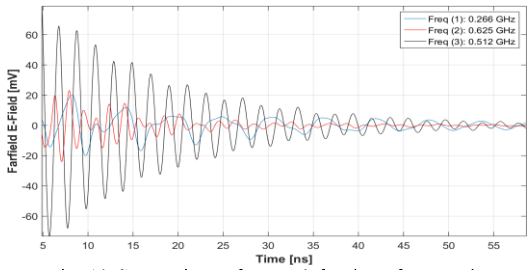

Fig. 10 Comparison of target 3 for three frequencies

The ambiguity in response to a non-CNR frequency is not unexpected: it was predicted in section II.B where it was noted that a multiple-peak spectral response, with a sinc function envelope, is characteristic of a coherent pulse train with square wave modulation. This spectral leakage means that some incident pulse energy may stimulate a late time response in the target at frequencies other than the carrier frequencies.

E. Target response to adaptive waveform shaping

The significant late-time response of target 2 at non-carrier frequencies (as shown in Fig. 9) was due to the fact that other target modes were stimulated by sidelobe energy around the carrier frequency. While some spectral leakage is unavoidable in a practical radar system, adjusting the period of the pulse and changing the waveform envelope to maximise the response of the targeted CNR significantly improves the target response at the resonant frequency (Fig. 11). The transmit waveform used to generate this result was a reversed-time version of the selected target CNR (i.e., with open-loop gain applied on the oscillation) as conceptualised in Fig. 5 above.

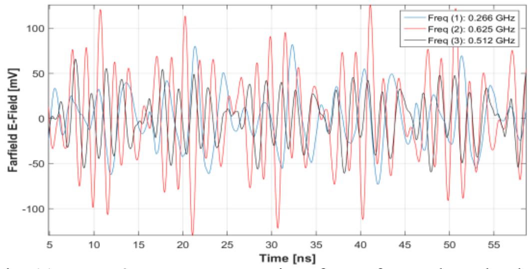

Fig. 11 Target 2 response to a series of waveform-adapted pulses

IV. DISCUSSION

The results obtained in this study show that the concept of targeted stimulation of late-time resonances by non-UWB radar systems is feasible. In order to develop a practical radar system based on these concepts, several issues need to be considered.

A. Accurate late-time observation

As the early time response of a target is not, in general, determined by the resonant frequencies of the target, and given that the early time is the dominant part of the overall target response, it is crucial that the late-time period can be isolated accurately in order to allow successful comparison of the late-time response when interrogating the target at a given narrowband frequency. Previous work by the authors has developed a method to isolate the late time start based solely on the target response [10], and adaptation of this method to a narrowband scenario is being examined.

B. Pulse Train Spectrum

Another, more serious complication, has been noted already. While the carrier frequency of a pulse train may be selected to match the particular resonant frequency of interest for target identification, the actual frequency spectrum of a coherent pulse train is more complicated than a single frequency CW signal.

It is clear that for a practical detection system there would be a need to selectively vary the carrier frequency, the PRF and the pulse width in order to target the selected resonant frequency while avoiding excitation of neighbouring frequencies that correspond to resonances of different targets. A library of known targets, and their respective dominant resonant frequencies, is required to facilitate the selection of these radar parameters. As the varying of the PRF and pulse width will have implications for other parameters of the radar system (e.g., maximum unambiguous range), selecting a resonant frequency for a target at a given range would present as a multi-parameter optimisation problem. Correct selection of carrier frequency, PRF and pulse width might even allow excitation of more than one resonant frequency at a time. Radar systems that incorporate pulse Doppler capabilities to discriminate moving targets from clutter typically employ staggered pulse repetition schemes to avoid the so-called “blind speeds” that occur when a constant PRF system is tracking a moving target [8]: again, we suggest that the set of pulse periods in such a scheme could be selected to incorporate excitation of the resonant frequencies of a given target.

C. Adaptive waveform shaping

A radar system employing the proposed selective resonant detection scheme would require a reasonably large library of potential targets in order to rapidly test for an unknown response; such a library, combined with the need for customised manipulation of the carrier frequency, PRF and pulse width, would add significantly to the complexity of the system, but would be within the capabilities of existing waveform agile radar systems. However, developing a system to adaptively shape the “time-reversed” pulses used to maximise a target mode would require a very high degree of adaptive capability. It is suggested that current developments in the area of Software Defined Radar (SDR [11]) will assist with this task, providing the flexibility to modify the transmit waveform with each time step to rapidly interrogate a series of CNR frequencies. Future work will focus on selection and optimisation of pulse waveform parameters to improve the selectivity of the radar for target CNRs.

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