Discrimination of Closely Resembling PEC Targets based on Natural Resonant Frequencies

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Abstract — The Natural Resonant Frequencies (NRFs) obtained from the late time response of targets are aspect independent in nature and thus, is well suited for radar target identification. In resonance based identification techniques, the accurate determination of NRFs is very important. In this paper, a technique for identifying the true NRFs of objects, useful in discriminating two closely resembling objects is proposed. The NRFs are extracted from the E-field response of the object using the Vector Fitting (VF) method. The NRFs of database object and the Radar Cross Section (RCS) of unknown object are used to discriminate between them. A risk factor is defined as a measure of discrimination. In this study, ellipsoids with different axial ratios are considered for discrimination and the results are presented.

Keywords— Natural resonant frequencies, radar target identification, risk factor, target discrimination, vector fitting.

I. Introduction

Accurate and automatic Radar Target Identification is the need of the day, in the present defense scenario, especially with the advent of stealth technology. In non-cooperative target recognition systems, the unknown targets are identified by comparing their features with a database of predetermined features of known targets. The features of a target extracted from backscatter responses should contain information about the physical and material properties of the target and should be aspect independent. The resonant frequencies contained in the late time response of an object depend on the size, shape and composition of the object [1]. Since these frequencies are independent of aspect angle, they form a good feature set for target identification. All resonance based identification techniques like the E-pulse technique require the natural resonant frequencies of the target to be determined accurately for correct identification [2]. For two objects of different shape and size, the resonances have large differences making the discrimination of such objects easy. However, discrimination of closely resembling objects is challenging as their resonances are closely placed. In this study, a technique to discriminate between closely resembling Perfectly Electrically Conducting (PEC) targets is proposed.

Techniques like the Prony's method and Matrix pencil method are available in literature for determining the poles of an object from the back scattered data either in the time or frequency domain [3]-[4]. Once the pole set that approximates the responses is determined, appropriate criteria are applied to select only those poles or resonances that characterize the target to a large extent. Vector fitting is a rational function approximation method which determines all the parameters of the transfer function model for a system, the poles, residues, and/or zeros, from the known frequency response of the system [5]. In this work, the Vector fitting method is used to determine the poles from the frequency response data of a target. The criteria for choosing the true NRFs, from the pole set (vector fitting poles), representative of targets shape and composition is proposed.

Ellipsoids of different axial ratios, with the major axis length constant, are considered as examples of objects with closely resembling shapes. The true NRFs of the ellipsoids are determined by applying the proposed technique. An ellipsoid of a/b ratio equal to 0.4 is considered as the standard target. The other ellipsoids are discriminated against the standard by determining the Risk which is defined later in the paper. The results of discrimination are presented.

II. Formulation of the Problem

In this section, we present briefly the criteria for choosing the true NRFs from vector fitting poles (VF poles). The discrimination technique is also discussed.

A. Extraction of Poles using Vector Fitting (VF)

Vector fitting is a rational function approximation method which relocates the N number of initial (starting) poles towards the actual poles iteratively. A general transfer function model of the kind shown in (1),

$$F(s) = \sum_{n=1}^{N} \frac{c_n}{s-a_n} + d + sh \tag{1}$$

can be modeled using VF, where c_n and a_n are the residues and poles respectively, and they may be real or complex conjugate pairs. The constants d and h are real quantities. In this work, the constants d and h are not considered.

The order of the poles N has to be optimally chosen. If N is less than the optimum number, the accuracy will suffer due to insufficient number of poles. On the other hand, too many poles, though do not reduce the accuracy, introduce more number of curve fitting poles (artifacts) [5]. The optimum value of N is chosen, such that the fitted function gives a small Root Mean Square Error (RMSE) value, and further increase

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in N does not lower the RMSE significantly [10]. The value of N that provides a RMSE value less than 1E-5 is considered as a good approximation for N in this study. These N poles contain both true poles that represent the target geometry as well as curve fitting poles.

B. Criteria for Extracting the True NRFs for target Discrimination

The true NRFs that are necessary for target discrimination purposes are identified from the pole set by applying the following criteria –

1) The target is a passive system, and can be considered as linear time invariant system which is inherently stable. Therefore, the system response contains only damped frequencies. Thus, only those poles that are complex and have negative real parts represent the true NRFs of the target.
2) The frequency response of a target is obtained at different aspect angles. The true NRFs appear in all the pole sets extracted from target's responses, irrespective of the aspects at which the responses are obtained. The true NRFs useful for discrimination can be identified as those which appear in every pole set.
3) The low frequency resonances characterize the crude shape of the scatterer, whereas the finer changes are present in the high frequency resonances. In order to discriminate closely resembling targets or targets with minor variations, both low and high frequency poles should be considered. In a way, it means that all the left half plane poles are to be considered. In order to reduce the number of NRFs, a single pole with the least damping is chosen for discrimination, from the poles that have nearly the same frequency, within 10% variation.

C. Discrimination Technique

The aim of the present study is to discriminate closely resembling targets by using the true NRFs. For completeness, a brief discussion of the technique used for discrimination is presented [7].

The discrimination technique involves building a database of distinction polynomials which is constructed using the true NRFs of the known target.

The distinction polynomial D (jw) is defined as

$$D(jw) = \prod_n (s - a_n)\ . \qquad (2)$$

Here, a_n are the dominant poles or true NRFs of the known target. The distinction polynomial may be approximated to a second degree polynomial when the frequencies approach the resonance frequencies ($w \approx w_n$). The RCS of the target is directly proportional to the square of the amplitude of the scattered field $|G(s)|^2$, where G(s) represents the transfer function of the target whose information about the shape and size is embedded in the form of poles of G(s).

The Risk Factor is defined as-

$$R_{td} = \int_{w_a}^{w_b} \left\{\frac{d^3}{dw^3}\left[|D_d(jw)|^2 . A_t(w)\right]\right\}^2 dw \qquad (3)$$

where, $D_d(jw)$ is the distinction polynomial constructed from the true NRFs of the known target, and $A_t(w)$ is the RCS data obtained from the unknown target in the frequency range w_a to w_b, at a particular aspect angle. In (3), we see that the term $[|D_d(jw)|^2 . A_t(w)]$ is a second order polynomial for ($w \approx w_n$) for correct identification, and the third degree differentiation should approach zero or a small value. When the poles of known target and unknown target are sufficiently different, the risk factor turns out to be a large value. The risk factor is thus used as a measure to discriminate two targets.

Two targets with structural variations, one regarded as a standard target and the other as a modified target are considered. The mono-static back scattered E-field data is obtained for the standard target at various aspect angles and for a range of frequencies. From the frequency response data, the poles of the standard target are determined using the VF algorithm. The true NRFs are then identified and the distinction polynomial D (jw) is constructed. The Risk factor of the modified target with respect to the standard target is calculated using the RCS data of the modified target and the distinction polynomial of the standard target as in (3). The difference of Risk in dB is then determined by

$$R_{in\ dB} = R_{tk} - R_{kk}\ . \qquad (4)$$

where, R_{tk} is the risk factor in dB of the modified test target with the known standard target and R_{kk} is the risk factor in dB for standard known target with itself.

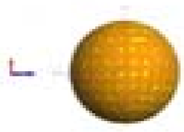
III. Results And Discussion

The true NRFs of PEC ellipsoids with major axis length of each equal to 10cm and axial ratios (a/b) equal to 0.2, 0.4, 0.6, 0.8 and 1 were determined from vector fitting poles, by applying the criteria discussed in Section II B. The details of the procedure to extract true NRFs is presented for ellipsoids of axial ratio equal to 1 (sphere of diameter=10cm), and 0.2.

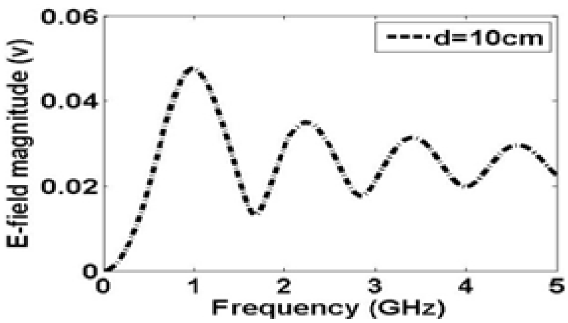
For the discrimination study, an ellipsoid with axial ratio 0.4 is considered as the standard target. Ellipsoids with ratios 0.2, 0.4, 0.6, 0.8 and 1, were discriminated against the standard object.

A. Determination of NRFs of PEC Sphere and Ellipsoids

The procedure to determine the true NRFs of a sphere from vector fitting poles is presented. The Model of a PEC sphere of 10cm diameter is shown in Fig 1.a. The far field response of the sphere, to an incident linearly polarized plane wave of 1V magnitude, was determined using commercially available electromagnetic simulation software [9]. The frequency response is obtained in the direction of incidence in the frequency range of 10MHz to 5GHz in steps of 10MHz.



(a)



(b)

Fig.1. a) Model of PEC sphere, b) its E-field response

The E-field magnitude response obtained for the sphere is shown in Fig 1.b. Using the frequency response data, the true NRFs of the sphere are determined using the vector fitting method. Four resonant peaks in the response suggest that N should be more than eight, considering each resonant frequency to be represented by complex conjugate pole pair. It was found that for N=18, RMSE=5.37E-7.

The poles extracted using vector fitting (VF poles) and the identified true poles are plotted in Fig 2.

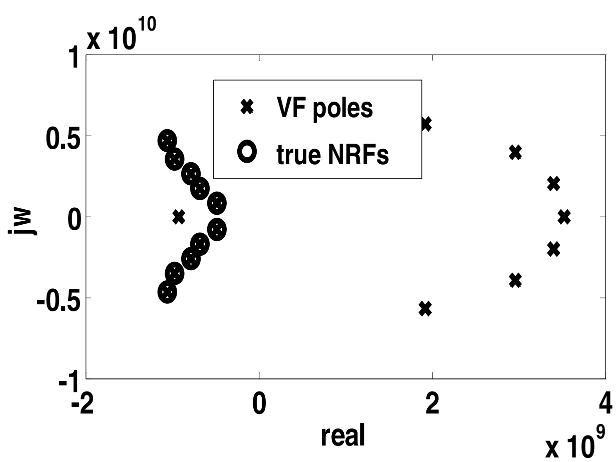
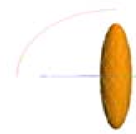


Fig.2. Identifying true NRFs of PEC sphere from VF poles

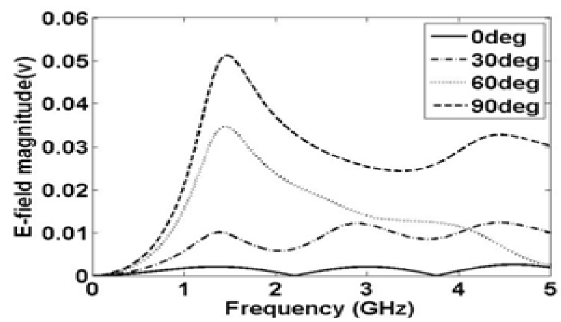
Among the total 18 poles extracted, 2 were real, 6 complex poles with positive real parts and another 10 complex poles with negative real parts. In the case of a sphere, because of its absolute symmetry, the poles on the left half plane are resolved and there are no two poles with the same frequency. Therefore, complex poles lying in the left half of s-plane and those within the frequency range of 10MHz to 5GHz are chosen as the true NRFs of the sphere.

A PEC ellipsoid of major axis length b=10cm and minor axis length a=2cm was similarly modelled and the poles were extracted using VF. In this case, the monostatic responses were obtained at $\emptyset=0^0$, $\theta= 0^0$, 30^0, 60^0 and 90^0 aspect angles ($\theta= 0^0$ is along the direction of major axis).

In Fig.3, the model and the E-field response at different aspects for ellipsoid of a/b=0.2 is shown. Fig.4 shows the plot of the VF poles and the true NRFs.



(a)



(b)

Fig.3. a) Model of ellipsoid (a/b=0.2), b) its e-field response at different aspect angles

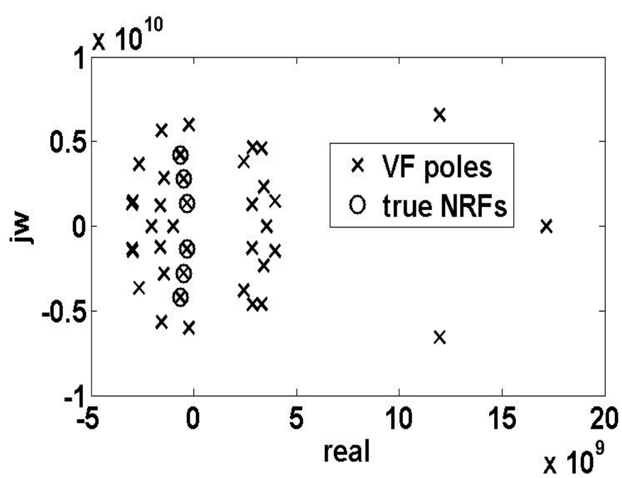


Fig.4. Identifying true NRFs of PEC ellipsoid (a/b=0.2) from VF poles.

The true NRFs were obtained for the other ellipsoids and the results normalized by 1E9 are presented in Table I. The NRFs obtained compare well with the values published in [8].

TABLE I
NRFs OF PEC SPHERE AND ELLIPSOIDS

NRFs of sphere a/b=1	**NRFs of ellipsoids of ratio a/b**			
	0.2	0.4	0.6	0.8
-0.4814±0.8303i	-0.3303±1.3564i	-0.4281±1.1626i	-0.4607±1.0362i	-0.4742±0.9255i
-0.6832±1.7241i	-0.5096±2.7739i	-1.3656±1.4993i	-0.8657±1.2208i	-0.7328±1.7313i
-0.7805±2.6506i	-0.6591±4.2028i	-0.7064±2.3653i	-0.7762±2.0613i	-0.8683±2.9384i
-0.9691±3.5158i		-1.0620±2.6566i	-0.8826±3.2082i	-1.2033±3.9706i
-1.0602±4.6654i		-0.7477±3.6038i	-1.1855±4.4817i	-1.2452±4.4889i
		-1.2112±4.9126i		

B. Discrimination Results

The discrimination technique discussed in Section IIC is implemented to discriminate closely resembling ellipsoids. All ellipsoids considered for discrimination had a major axis (b) of 10cm length and only their minor axis (a) length was varied. The ellipsoid of a/b ratio = 0.4 was considered as the standard target. The risk factor for discriminating the other ellipsoids of axial ratios: 0.2, 0.4, 0.6, 0.8 and 1, were determined. The distinction polynomial for 0.4 ratio ellipsoid (standard) was built using the NRFs that were determined (Table-1). The RCS of all other test targets was obtained at $\theta = 0^0$ and 30^0 aspect angles. Then, the risk in dB was calculated using (5). The discrimination results are presented in Table II. A discrimination of more than 15dB was obtained in each case.

TABLE II
DISCRIMINATION RESULT

Ellipsoids discriminated a/b ratios	**Risk in dB [of identifying with ellipsoid of a/b=0.4]**	
	$\theta=0^0$	**$\theta=30^0$**
0.2	24.39	33.15
0.4	0	0
0.6	22.36	21.83
0.8	21.02	28.09
1	16.83	16.83

IV. CONCLUSIONS

The aim of the present study is to identify a reduced set of true NRFs of an object, and to discriminate closely resembling objects using them. In this study, both the low and high frequency poles are considered to enable distinction in the crude shape as well as the finer aspects of the object. The pole set is further reduced by representing all poles of nearly same frequency by a single pole which has the maximum influence on the response. This reduces the number of NRFs needed to build the distinction polynomial of database targets.

The discrimination results obtained shows that the discrimination of objects resembling closely in shape and size is possible by the technique proposed.

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