TECHNIQUE OF ULTRA WIDEBAND RADAR TARGET DISCRIMINATION USING NATURAL FREQUENCIES

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Abstract: *An aspect independent radar target discrimination method based on the natural frequencies of ultra wideband radar targets is introduced. The sets of points in multi-dimension space corresponding to the poles on complex plane (natural resonances) were offered as signatures of radar targets. This approach allows performing the automated discrimination algorithm of radar targets. The results of experimental research of the signals scattered by scaled aircraft models using the signatures algorithm and cumulant preprocessing are presented.*

I. INTRODUCTION

Recently many radar target discrimination methods using the ultra wideband response of a target to a transient incident waveform have stimulated growing interest [1], [2]. The Baum's singularity expansion method (SEM) [3] provides the necessary mathematical formulation for describing the transient behavior of conducting targets. The late-time response of the target can be represented as a sum of natural modes,

$$y[n] = x[n] + w[n] = \sum_{k=1}^{K} A_k e^{-\sigma_k n T_o} \cos\left(2\pi f_k n T_o + \varphi_k\right) + w[n], \tag{1}$$

where $s_k = \sigma_k + j2\pi f_k$ is the k-th aspect-independent natural complex frequency of the target, and A_k and φ_k are the aspect- and excitation-dependent amplitude and phase of the k-th target mode, respectively, $w[n]$ are samples of additive Gaussian band-limited noise. T_o describes the period of sampling. The number of natural frequencies K is determined by the finite bandwidth of the waveform exciting the target. These frequencies are determined by basic geometrical sizes and shape of objects, practically do not depend on an aspect angle and can be used for discrimination of the radar targets.

Traditional parametrical methods can be used for the estimation of finite number of parameters describing an ultra wideband radar target, for example, the well-known Prony's method, pencil-of-function method, ESPRIT.

In our previous works it was shown that the higher order statistics have the following characteristics [4]:

- cumulants of Gaussian processes of order greater than two are zero and so they can be used to suppress noise under certain conditions;
- cumulants of non-Gaussian processes include higher order statistical information about the signal.

So the higher order cumulants can greatly suppress the additive Gaussian noise presented in measured response of ultra wideband radar targets.

The discrimination technique using signatures algorithm is described in this paper. These signatures are the points in multi-dimensional attribute space, each axis of which is proportional to the true value of poles' coordinates on a complex z-plane for the expected target. The distance between an estimation of a point in attribute space of the identified object and the signatures of objects stored in a databank is the criterion for its discrimination. Such approach allows creating the automated system of ultra wideband radar target discrimination.

The paper is organized as follows. In section II, the resonant model of ultra wideband radar targets is presented. Section III describes the radar target discrimination algorithm. The results of experimental research of signals scattered by the scaled aircraft models are presented in Section IV. Concluding remarks are drawn in Section V.

II. THE RESONANT MODEL

According to the SEM, the system transfer function of object completely characterized by a set of natural frequencies on complex s-plane. The resonant frequencies band of radar targets with the characteristic sizes from 0.1 up to 10 meters lies in the range from units up to hundreds of megahertz.

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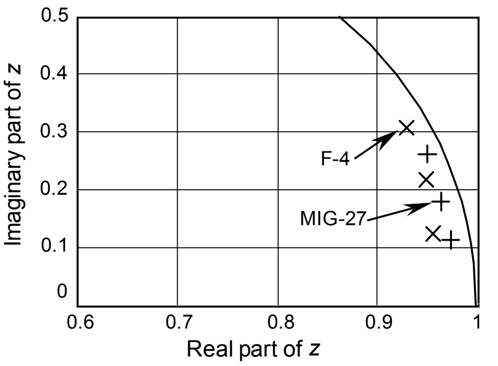

Fig. 1. Complex z-plane plot of aircraft models

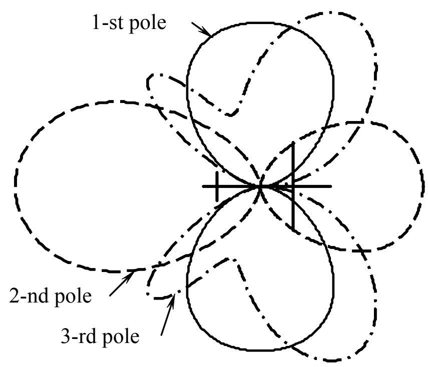

Fig. 2. The resonant poles' residues dependence on aspect angle

To make the analysis of ultra wideband radar target discrimination algorithm we have selected resonance frequencies [2], appropriate to resonances of F-4 and MIG-27 scaled aircraft models. Fig. 1 shows the locations of resonant poles on the complex z-plane for these targets. The relative values of poles

$$z_k = \exp\{(\sigma_k + j2\pi f_k)T_o\}. \tag{2}$$

Fig. 2 shows the resonant poles' residues dependence on aspect angle.

III. Radar Target Discrimination

In this paper the following task is considered. It is necessary to discriminate the given number of radar targets by using measured ultra wideband responses of objects. It is supposed, that these objects are a priori divided into M classes. The set of the measured natural poles $z_1, z_2, \ldots, z_N$ is used as attributes of the chosen targets' classes, or as a dictionary of attributes.

The number of attributes N (the dimension of the attributes' dictionary) is determined by the given set of classes and depends on used discrimination algorithm. The expression determining classes of radar targets can be written in language of these attributes.

Generally it is necessary to minimize the attributes number N, which is describing the object, because it simplifies discrimination algorithm of ultra wideband radar targets. Definition of optimum number N is one of tasks of our research. A point in N-dimensional space of attributes represents each class of identified objects

$$\bar{S}_j = \{S_{j1}, S_{j2}, \ldots, S_{jN}\}, \tag{3}$$

where S_{ji} is the appropriate coordinate in space of attributes, $j = 1\ldots M$.

The measured set of attributes for the real response from ultra wideband radar target differs from each set of classes' attributes, as the signal is corrupted by noise:

$$\bar{Y}_j = \bar{S}_j + \bar{W}, \tag{4}$$

where $\bar{Y}_j$ is the set of measured attributes $\bar{Y}_j = \{Y_{j1}, Y_{j2}, \ldots, Y_{jN}\}$, $\bar{W}$ is an error in attributes' estimation because the noise is present in the received signal.

The correspondence of the measured set of attributes $\bar{Y}_j$ to one of the given classes of the targets $\bar{S}_j$ (or the decision criterion) is following. The space of attributes is divided into M of the not crossed areas appropriate to chosen classes of the targets. The borders of these areas are determined by the solution of optimization problem: decision Γ_j on identification of j-th class of the targets is accepted for set of the measured parameters $\bar{Y}_i$ in case if the distances R_i between $\bar{Y}_i$ and $\bar{S}_j$ in space of attributes is minimally in comparison with distances up to all other signatures:

$$R_i = \left|\bar{Y}_i - \bar{S}_j\right|, \quad j = 1, \ldots, M. \tag{5}$$

Quality of ultra wideband radar targets discrimination algorithm is estimated by probability of true discrimination for the targets of all classes:

$$P_{true} = \sum_{i=1}^{M} P_i \cdot P(\Gamma_i / H_i), \tag{6}$$

where P_i is a priori probability of i-th class, $P(\Gamma_i/H_i)$ is the conditional probability of decision making Γ_i provided that is put forward hypothesis H_i about identification of the i-th class is true.

The probability of true discrimination is determined by dimension of the dictionary of attributes, i.e. the number of the measured natural poles of the target, and depends on noise level $w[n]$ present in the data. Therefore it is important to define of the boundary signal-to-noise ratio at which the given level of probability of true discrimination is provided.

The probability of true discrimination at the given signal-to-noise ratio depends on the number of significant attributes N and on their concrete choice from K measured natural frequencies of discriminations target. The influence of the number of significant attributes and of the concrete parameters of resonant model for chosen value N on the probability of true discrimination is presented.

IV. Results of Digital Modelling

For an experimental research of ultra wideband radar target discrimination algorithm the responses of the scaled models of planes F-4 and MIG-27 were used. Independent Gaussian band-limited noise sequence each run was perturbed. The signal-to-noise ratio SNR was estimated as

$$\mathrm{SNR} = 10 \cdot \lg\left(\frac{\mathrm{M}\left(x^2[n]\right)}{\mathrm{M}\left(w^2[n]\right)}\right), \tag{7}$$

where M(•) denotes the mean value.

The results of F-4 resonant model poles estimation by pencil-of-function [5] method for 500 independent realizations of signal with Gaussian band-limited noise with signal-to-noise ratio SNR = 10 dB are depicted in Fig. 3. The true signal poles locations are depicted as circles, the estimations are shown as points. From figure it is visible, that estimations for high-frequency (HF) poles are concentrated near the true value while estimations of mid-frequency (MF) and low-frequency (LF) poles have much more dispersion.

The set of the measured natural poles on complex plane were used as information parameters in a dictionary of attributes for the radar targets. The resonant models of both targets consist of three pairs of complex conjugate poles, so a maximum quantity of attributes is $N = 6$.

We analyses dependence of probability of true discrimination of radar targets on the signal-to-noise ratio at different quantity of the information attributes N, depicted on fig. 4. From figure it is visible, that at reduction N for the fixed signal-to-noise ratio the probability of true discrimination is increased. It shows that the task of discrimination of ultra wideband radar targets may be solved by the best way at $N = 2$, if the HF pole is present in each case.

Probabilities of true discrimination of the radar targets from the signal-to-noise ratio for the specified types of poles are presented on Fig. 5. From figure it is visible, that the maximal probability of true discrimination is provided with a high-frequency pole. It is possible to explain this by highest Q-factor of the high frequency pole in our model. The Q-factor of a resonant model's pole is the following ratio:

$$\mathrm{Q}_k = \frac{\omega_k}{2|\sigma_k|} = \frac{\pi f_k}{|\sigma_k|}. \tag{8}$$

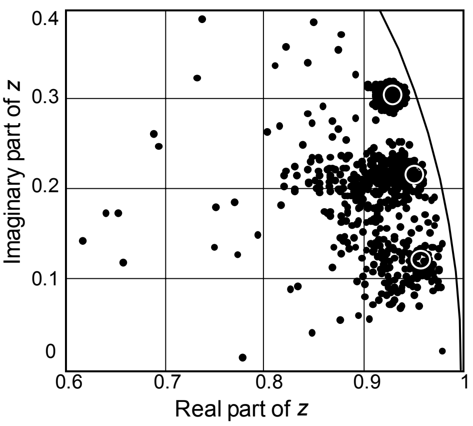

Fig. 3. Estimates of poles for 500 independent runs using pencil-of-function method, SNR = 10 dB

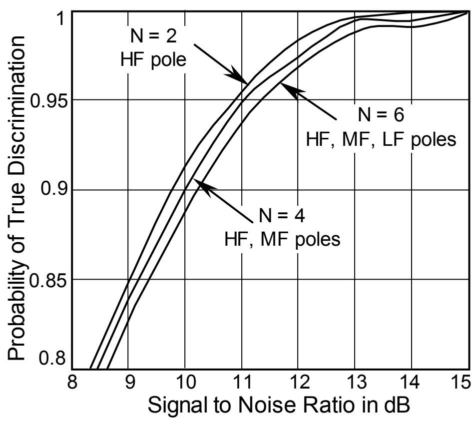

Fig. 4. Probability of true discrimination for several numbers of quantities of attributes N

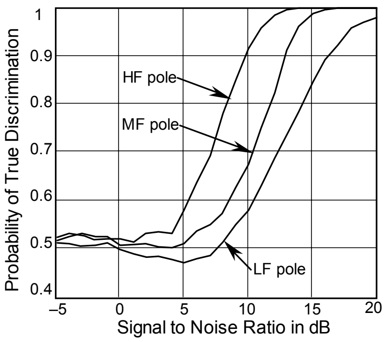

Fig. 5. Probability of true discrimination for single poles of resonant models

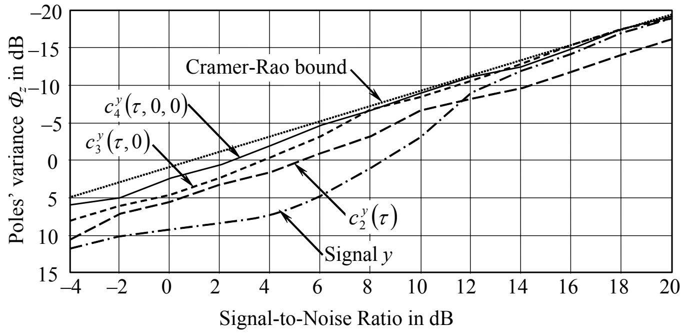

Fig. 6. The variance of the resonant model poles

The quantitative comparison of effectiveness of the discrimination algorithms can be made by using the relative poles' variance:

$$\Phi z_k = 10 \cdot \lg \sum_{i=1}^{L} \left\{ \frac{1}{L} \frac{\left| z_{k,i} - z_k \right|^2}{\left| \sigma_k \right|^2} \right\}, \quad (9)$$

where z_k is k-th pole of the signal; $z_{k,i}$ is estimation of k- th pole for i-th trial run of $y[n]$ (1); L is a number of independent trial runs. Each sample of variance was computed by L = 500 trial runs. Independent Gaussian band-limited noise sequence each run was perturbed.

Fig. 6 shows the dependences of a total resonant models poles' variance on the signal-to-noise ratio for the higher order cumulant sequences of ultra wideband radar targets. One can see that for all signal-to-noise ratios the best quality of resonant model poles' estimation provides the 1-D slice of the fourth order cumulant sequence $c_4^y(\tau, 0, 0)$. So the higher order cumulants can be used as an effective tool for improving the discrimination of ultra wideband radar targets in the passive and active radar systems.

V. Conclusions

An aspect independent radar target discrimination method based on the natural frequencies of ultra wideband radar targets is presented. The sets of natural resonances were offered to use as signatures of radar targets.

The main results of our researches are following:

– for the chosen resonant models of scaled planes F-4 and the MIG-27 it is shown, that the increase of dimension of attributes' space results in deterioration of probability of true discrimination. So, for the signal-to-noise ratio SNR = 10 dB reduction N from 6 up to 2 leads to increasing P_{true} from 0.88 up to 0.92;

– at the given quantity of information attributes $N = 2$ probability of true discrimination depends on the chosen pole. So, for the signal-to-noise ratio SNR = 10 dB the gain due to the correct choice of the pole may reach 0.33, i.e. from $P_{true} = 0.57$ up to 0.9;

– the results of digital modeling show that the using of the fourth order cumulants method for parameter estimation of the resonant model leads to the increase of the poles' accuracy estimation by 5-10 dB in comparison with traditional algorithms.

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