CONSTRUCTION OF TRAINING DATABASE BASED ON HIGH FREQUENCY RCS PREDICTION METHODS FOR ATR

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Abstract—Due to the difficulty of creating training databases using all real enemy targets, it is necessary to derive them using computer simulations. In this paper, we apply three high frequency radar cross section (RCS) methods to create a training database for automatic target recognition (ATR) using 1-D range profiles. These methods are: physical optics (PO), physical theory of diffraction (PTD) and shooting and bouncing ray (SBR). Experimental results derived from the performance of combinational feature space trajectory with a new distance metric (FSTND) classifier show that PO+PTD is the most efficient method for ATR because of the additional information by diffraction terms. SBR shows poor performance due to the cavity structure.

1. INTRODUCTION

For air-to-air or land-to-air target recognition, research on automatic target recognition (ATR) of targets using one dimensional range profiles [1] has been active for several decades due to the simplicity and fast calculation. Currently, objects can be successfully classified more than 80% of the time using multiaspect range profile information [2]. However, the training data used were obtained by measuring actual models, which is not practical because of cost and
confidentiality. Many comparisons between the prediction method and the measurement of radar cross section (RCS) have been published to solve this problem and much work has been done to evaluate the prediction method in regards to ATR. However, not much of the latter has been reported due to the sensitive military application of this topic. In this paper, considering the X-band operation of the normal tracking and air-to-air radars and larger military targets than the wavelength, we evaluate three high frequency RCS prediction methods: physical optics (PO) [3, 4], physical theory of diffraction (PTD) [5, 6] and shooting bouncing ray method (SBR) [7, 8] on ATR. The training data from PO, PO+PTD, SBR, and SBR+PTD were utilized for ATR of 5 scale models. Then measured test data from compact range were inserted into a combinational feature space trajectory classifier with a new distance metric (FSTND) [2]. Experimental results show the importance of PTD and poor performance of SBR.

2. PREDICTION METHODS, FEATURE EXTRACTION AND CLASSIFICATION

2.1. High Frequency RCS Prediction Methods

Physical Optics (PO) is a current-based approximation where the body currents generate scattering of a target. In PO approximation, the scatterer is assumed to be much larger than the wavelength and the surface of the scatterer is modeled as a set of polygons, normally triangles and rectangles. In addition, far field condition (plane waves) is assumed and the observation point is fixed to z axis. Then after mathematical manipulations, the horizontal and vertical components of scattered field for a single facet with area $F_p$ can be expressed as follows [9]:

$$\begin{bmatrix}
    E_{sh} \\
    E_{sv}
\end{bmatrix} = \frac{jke^{-jkr}}{2\pi} \int_{F_p} e^{2jkr'} dx' dy' \times \begin{bmatrix}
    R_H n_x^2 - R_E n_y^2 (R_H R_E) n_x n_y \\
    (R_H R_E) n_x n_y R_H n_y^2 - R_E n_x^2
\end{bmatrix} \begin{bmatrix}
    E_{ih} \\
    E_{iv}
\end{bmatrix}$$

where $n_x, n_y, n_z$ are the $x, y$ and $z$ components of the unit normal vector on the patch. $R_H$ and $R_E$ are the reflection components of $H$ and $E$ polarizations. The phase integral in this equation can be calculated using the phase integral algorithm. To apply this to any arbitrary structure, all invisible facets are removed and the total reflected field is the summation of those calculated from all visible
facets. The endpoint phase integral is in closed-form and includes specular return and diffraction terms.

The diffraction included in PO endpoint integration cannot accurately predict diffraction by the nonuniform edge current. Physical theory of diffraction (PTD) methods can predict the diffraction more accurately. In this paper, we use method of equivalent current (MEC) devised by Ryan and Peters and extended to the 3-dimensional case by Knott and Senior [5, 6].

Geometric Optics (GO) theory explains reflections such as occur at dihedral corner reflectors. GO maintains the planar nature of a wave upon reflection from a facet and then by using PO, a phase integral can be performed on the successive reflective facets. Shooting and bouncing ray (SBR) method utilizes this GO-PO method by discretizing the incident wave with a grid size smaller than $\lambda/10$ [7, 8]. However, this method has the disadvantage of long computation time.

### 2.2. Feature Extraction and Classification

After range profiles are calculated using high frequency RCS prediction methods and inverse fast Fourier transform (IFFT), the central moments of the normalized range profiles are used to constitute feature vectors to obtain both scale and translation invariance. The $p$th order central moment of a range profile [10] can be computed by

$$
\mu_p = \sum_{i=1}^{N_r} (r_i - \eta_r)^p \left[ \frac{\overline{p}_m(r_i)}{\sum_{i=1}^{N_r} \overline{p}_m(r_i)} \right],
$$

where

$$
\eta_r = \sum_{i=1}^{N_r} r_i \left[ \frac{\overline{p}_m(r_i)}{\sum_{i=1}^{N_r} \overline{p}_m(r_i)} \right], \quad r_i \in [0, R_u]
$$

$\overline{p}_m(r_i)$ is the normalized range profile, $N_r$ is the number of range bins and $R_u$ is the maximum unambiguous range. Using these central moments, feature vectors are made as follows:

$$
f = [\mu_1 \mu_2 \ldots \mu_{p_{max}}]^T
$$
where $p_{\text{max}}$ is the maximum order of central moments in the feature vector. Preliminary trials showed that 20 is sufficient for classifying 1-D range profiles. The total train data of $N_c$ targets and $N_a$ angles are obtained as follows:

$$F = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1,N_c \times N_a} \\ f_{21} & f_{22} & \cdots & f_{2,N_c \times N_a} \\ \vdots & \vdots & \ddots & \vdots \\ f_{p_{\text{max}},1} & f_{p_{\text{max}},2} & \cdots & f_{p_{\text{max}},N_c \times N_a} \end{bmatrix}$$

Then principle component analysis (PCA) is utilized to compress the feature vectors. After deriving the transformation matrix $P(p_{\text{max}} \times l)$ by using the covariance matrix of training data set, a new transformed train and test data set of smaller dimension $l$ is derived as follows:

$$x_k = P^T \overline{f}_k$$

where $\overline{f}_k$ is the normalized feature vector.

For the classifier, we utilize the combinational feature trajectory concept (FST) classifier with a new distance metric (FSTND), which is very efficient in classifying multiaspect range profiles. Classification uses the distance between a line segment of each feature space trajectory and the one connecting two vertices of a test trajectory [2]. Fig. 1 shows the overall classification procedure.

![Figure 1. Classification procedure.](image-url)
3. EXPERIMENTAL RESULTS

Fig. 2 shows the five aircraft-like models used for classification experiments. Target 1 simulates normal civil airplanes; target 2 simulates fighters. The inlets are included to observe the effect of multi-bouncing, which is a main source of scattering on the aircraft. Targets 3 and 4 were designed to test whether adjusting the location and shape of the inlets affects the ability of these methods to classify

(a) target 1
(b) target 2
(c) target 3
(d) target 4
(e) target 5

Figure 2. Five scale models used for classification.
targets. Target 5 simulates normal missiles which have very little multi-bouncing. The frequency bandwidth of the simulation ranges from 8.3 to 12.3 GHz (X-band) in 0.01-GHz increments, yielding 401 frequency domain samples. The range resolution of this setup is 3.75 cm. Aspect angles range from 0° to 45° with respect to the head-on direction in 0.5° increments (91 aspects for each data). For polarization, horizontally transmitting-horizontally receiving (HH) was utilized. After obtaining training data through simulations with each high frequency prediction method, experiments using the five targets were performed in the compact range of Pohang University of Science Technology (POSTECH) with the same parameters. PTD terms were added to PO and SBR to constitute the data of PO+PTD, PO+SBR. Then, the frequency-swept data of both prediction and measurement were processed to calculate range profiles and central moments and stored as training and test data to be input into the combinational FSTND classifier. In deriving central moments, 100 independent calculations were performed with independent additive white Gaussian noise (AWGN) at SNRs 0, 5, 10, 15, 20 dB.

Fig. 3 presents the variation of range profiles of target 1 using each high frequency prediction method and measurement as the aspect angle varies from 0° to 15° in 0.5° increments. In all five subfigures, peak values appear at three dominant scattering center locations, 12.8 m (nose), 13.2 m (inlet structures on wings), and 13.6 m (main body) even though overall distributions are different from one another. These three scattering centers are marked as 1⃝, 2⃝ and 3⃝. At the 0° aspect angle (head-on), peak values appear at three scattering center locations in all figures due to large specular returns. As the aspect angle increases slightly (0° ∼ 3°), multi-bouncing terms from inlet structures contribute more to the measured data on corresponding position 2⃝. Therefore, high range profile values occur on 2⃝ in measured data. In PO and PO+PTD, such multi-bouncing effects do not occur because these methods consider only specular returns and diffractions. In SBR and SBR+PTD, high values also do not occur on 2⃝ even though these methods consider multi-bouncing effects. In fact, the accuracy of SBR method is limited because GO neglects the fields that are coupled into the interior of the cavity via diffraction by the edges at the open end. The results are reasonably accurate as long as these diffraction fields are significantly weaker than the GO fields which generally dominate inside electrically large cavities. To overcome the limitations of GO, methods such as the Gaussian beam shooting technique, the generalized ray expansion (GRE) method and iterative PO (IPO) have been devised [13–15]. Of these methods, IPO is the most accurate. As the aspect angle increases, multi-bouncing effects contribute less and
Figure 3. Variation of range profiles of target 1 in each method as aspect angle varies
specular returns again become the dominant component of scattering. Therefore, PO and PO+PTD show similar peaks to those measured, especially at $\theta_1$ and $\theta_3$. Therefore, we conclude that specular returns are very important factors in calculating range profiles and that other methods are needed to calculate multi-bouncings from inlets.

![ISAR images of target 1 and 4](image)

**Figure 4.** ISAR images of target 1 and 4

Fig. 4 shows the ISAR images of target 1 and 4 [11, 12]. In this figure, PO and PO+PTD were compared using target 1 and for SBR and SBR+PTD, target 4 was used. Figs. 4c and 4f demonstrate that diffraction occurs on the nose, tips of fuselage, wings and stabilizers. In (a), PO doesn’t correctly show the effect of diffraction by the nose and the tips of wings. Although some diffraction-like terms are seen in tail stabilizers, they are negligible. In the figures of PO+PTD of target 1 (b) and SBR+Diffraction of target 4 (e), diffractions occur in the proper locations, such as stabilizers located in the tail, making the image more similar to the measured one. Especially compared with PO and SBR, we infer that the location and amplitude of peaks caused by diffractions from tails can give important information for target classification.
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Figure 5. Classification result

Classification ratios in Fig. 5 confirms conclusions from Fig. 3 and Fig. 4. Comparing classification results of PO and SBR confirms our conclusion from Fig. 3 that the specular return component (PO) is an important factor in constituting range profiles in wide aspect angles and SBR is inappropriate for ATR due to the cavity structure. In addition, considering classification ratios using PO+PTD and SBR+PTD are higher by 10 ∼ 15% than their counterparts without PTD, we also confirm the importance of additional information given by diffraction terms, especially those from tails. From this classification result, we conclude that the combination of PO and PTD is the best of these four high frequency prediction methods for creating training database for ATR.

4. CONCLUSION

In this paper, principles of three high frequency RCS prediction methods, PO, PTD and SBR, were applied to ATR of aircraft-like targets to quantify the effects of three major scattering mechanisms: specular return, diffraction and multi-bouncing. Results show that in the ATR using 1-D range profiles, specular returns and diffractions (PO+PTD) were the most effective method to create a training database for ATR in wide aspect angle range. By comparing the results of PO+PTD and SBR+PTD with their counterparts without PTD, we detected the importance of diffraction terms on the classification ratios.
In addition, we showed that SBR was not adequate for constituting training database for ATR because GO neglects the fields coupled into the interior of the cavity via diffraction by the edges at the open end.

REFERENCES


