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Accurate scattering centers modeling for complex conducting targets based on induced currents

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Dear editor,

According to the electromagnetic theory, each scattering center (SC) is equivalent to a mathematical discontinuity in Stratton-Chu integrals [1]. From the view of geometrical structure, the positions of SCs correspond to the discontinuities of surface and specular points. Therefore, the signatures of SCs in radar images can represent the actual geometric characteristics. Three-dimension SC model has been successfully applied for the radar target reconstruction and automatic target recognition (ATR) [2].

For separating independent contributions of SCs from the total scattering field, two methods are available. The first is based on high-resolution images such as the time-frequency representations (TFRs) [3]. In this method, locations and amplitudes of SCs are extracted from radar imaging results. As a consequence, the extraction precision is limited by the image resolution. The second method is based on the geometric partition of the target [4]. In this method, local contributions of SCs are analyzed by scattering mechanisms or computed by high-frequency methods such as ray tracing method [5]. This method is not restricted by the image resolution but the accuracy is limited by high-frequency asymptotic methods used in the computation of local scattering fields.

To address the above problems in the SC modeling of complex targets, a method based on the induced currents is proposed in this letter. The SC modeling includes both selecting suitable mathematic model according to the type of SCs and extracting the unknown parameters of the model. To assure the precision of scattering computation, we apply the full-wave numerical method to compute the induced currents on the target [6]. Then the independent scattering contributions of each SC are obtained through the procedure of geometrical partition, combination and selection.

Compared with traditional methods, there are three advantages in this method. Firstly, because the variation of induced currents is less than the fluctuation of scattering fields and the range of Doppler frequency of each partition is less than that of the total target, the scattering results of sparser incident angles are required in this method than those in radar imaging. Thus, the amount of computation can be decreased largely. Secondly, through classification, partition and subdivision, the number of SCs in each region is reduced greatly. This is beneficial to the parameters estimation since the interference of other SCs in radar images can be avoided mostly. Thirdly, the SCs of all partitions can be ranked according to their contributions to the total fields, so the accuracy of simulation can be controllable through selecting the number of SCs.

Taking a quadrotor, which is widely used in both military and civil fields [7], with complex structures as an example, the implementation of the proposed method is presented. The numerical results demonstrate the accuracy of the built SC model in simulation of signatures in inverse synthetic aperture radar (ISAR) images.

Model and methodology. In general, SCs are divided into three categories: local scattering centers (LSCs), distributed scattering centers (DSCs) and sliding scattering centers (SSCs). LSC is located at a fixed spot on the target, and the amplitude of LSC varies slowly with the aspect angle; DSC is located within an extended region, and it can only be observed in a narrow angle range; SSC slides on smooth surface or curved edge when the aspect angle varies. The expression of scattering fields of SCs is given as

$$E(f,\xi)=\sum_{i=1}^{N}A_i(\xi)\left(\frac{\mathrm{j}f}{f_c}\right)^{\alpha_i}\mathrm{e}^{2\mathrm{j}k\boldsymbol{r}_i(\xi)\cdot\hat{\boldsymbol{r}}_{\mathrm{los}}},\tag{1}$$

where $\xi=(\theta,\phi)$ denotes the radar aspect angle of the line of sight (LOS). $A_i(\xi)$ is the scattering amplitude of the ith SC, which is in different expressions for LSC, DSC and SSC. α is the frequency dependent factor and varies according to the scattering mechanism. $\boldsymbol{r}_i(\xi)$ is the position vector, which is a constant for LSC and DSC.

The attributes of three SCs are related to the geometric structures. The geometric structures of LSCs include end-point, corner, small gap or projection; the structures of DSCs include straight edge, planar surface and single-curved

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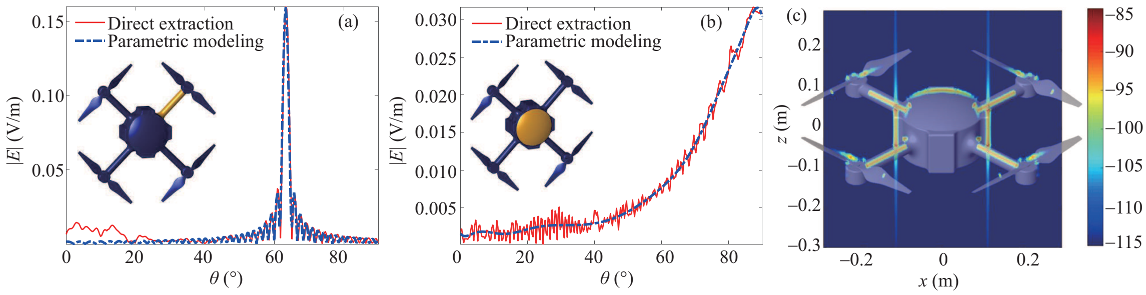

Figure 1 (Color online) (a) The scattering amplitude and the modeling result on a wing arm (Region 37); (b) the scattering amplitude and the modeling result on the top surface (Region 50); (c) the ISAR image of the quadrotor.

surface; the structures of SSCs include curved edge, single-curved surface and double-curved surface. For conducting targets, the attributes of SCs are actually determined by the distribution characteristics of induced currents. The uniform currents on planar surface form the DSCs; the non-uniform currents on the geometric discontinuities form the LSCs; the currents in the first half-wave zone centered on the stationary phase point contribute to forming the SSCs. In more detail, different types of current partitions corresponding to different scattering mechanisms and SC types are presented in Appendix A. In order to obtain the individual contributions of SCs, we devide the induced currents on the target into small regions according to the type of geometric structure. Then scattering fields of each small region can be calculated by the integral formulation for the far-field conditions as presented in Appendix B.

In order to judge whether there is only one SC existing in each region, the TFR of the scattered fields from the region is used here. The case of multiple SCs shown in the TFR indicates that there are multiple elementary structures and geometric discontinuities combined in the region. To deal with this problem, we subdivide the region according to the degree of deviation between the normal directions of adjacent facets. By refining the region, the scattering contribution of every individual SC can be obtained, and then the parameters of the SC model can be extracted. Compared with the method of extracting parameters of SCs from the total fields, the error of parameter estimation caused by the overlapping of multiple SCs can be effectively avoided.

Using computer-aided design (CAD) softwares such as ANSYS and CATIA, the process of partition based on geometric types can be implemented easily. In the geometric modeling, different types of geometric structures are built as independent element. The rules of the sequential index of the meshed facets in element structures make it easy to implement the geometrical partition. Another benefit of such indexing rules is the convenience in selecting the current data in each region to calculate the corresponding scattering fields.

As a sum, the SC extraction method based on the induced currents includes the following steps.

- Step 1. Mesh the complex targets with triangular facets in CAD softwares.
- Step 2. Compute the induced currents and establish the database of the currents under required aspect angles and frequency.
- Step 3. Partition the target geometry according to element structures (or the degree of deviation between the normal directions of adjacent facets for refining), and then the currents of each partition are applied to calculate scattering fields and TFRs.
- Step 4. Apply the time-frequency transform to judge whether there is only one SC in each region. If multiple SCs occur in one region, the corresponding geometric partition needs to be further refined and we return to Step 3.
- Step 5. Rank the SCs according to the amplitude of scattering fields. If the amplitude is less than a threshold which means this region has little contribution to total fields, it will be neglected in subsequent modeling.
- Step 6. Determine the type and location of each SC according to the geometrical structure together with the image signatures shown in TFRs.
- Step 7. Select the suitable parametric model for each SC, and estimate the parameters of the model from scattering fields of each region.

Numerical results. Take a typical multi-scale target, a quadrotor, to validate the precision of the proposed method. The overall size of the quadrotor is 0.7 m and the electrical size is 105λ when the frequency is 45 GHz. The largest structure is the top surface in the center of the quadrotor, with a diameter of about 0.2 m (30λ). The diameter of the axle is 0.018 m (2.7λ).

Based on the degree of deviation between the normal directions of adjacent facets, the partition of the quadrotor is accomplished. The degree of normal deviation is expressed by the dot-product value of two normal directions. Finally, the quadrotor is partitioned into 53 regions and then we select 21 regions comprising of 21 SCs (including 10 LSCs, 3 DSCs, and 8 SSCs) for the incident aspect angle range of $\theta = 0°$–$90° (\Delta\theta = 0.3°), \phi = 60°$. The more specific partitioning process and result are presented in Appendix C.

Figures 1(a) and (b) show good agreement between scattering fields calculated directly from the accurate induced currents and modeling. Their SC models and estimated parameters are given below:

$$E_{37}(f,\theta) = \left(\frac{\mathrm{j}f}{f_c}\right)^{\alpha_0} A_0 \mathrm{sinc}[L_0 k \sin(\theta-\theta_0)] \mathrm{e}^{2\mathrm{j}k\boldsymbol{r}_{37}\cdot\hat{\boldsymbol{r}}_{\mathrm{los}}},$$
$$E_{50}(f,\theta) = A_{50}(\theta)\mathrm{e}^{2\mathrm{j}k\boldsymbol{r}_{50}(\theta)\cdot\hat{\boldsymbol{r}}_{\mathrm{los}}}, \tag{2}$$

where $\alpha_0 = 0.5$, $A_0 = 0.1598$, $L_0 = 0.0364$ and $\theta_0 = 63.3°$. The position vector $\boldsymbol{r}_{37} = [-0.1405, 0.0, 0.1405]$. The surface in Figure 1(b) is double-curved, so the frequency dependent factor α is 0. The amplitude in Region 50 is expressed by the polynomial, $A_{50}(\theta) = \sum_{i=1}^{N} p_i \theta^{i-1}$. The variation of the position in Region 50 is also expressed by the polynomial, and the extracted parameters are described in Appendix D.

The ISAR image with a bandwidth of 30 GHz is shown in Figure 1(c). Compared with the actual quadrotor, it can be found that the main geometric structures are reflected in the ISAR image evidently, which proves the accuracy of the SC model in ISAR signature simulation.

Conclusion. An SC modeling method is proposed based on the induced currents on the target. The induced currents computed by full-wave numerical method assure the modeling precision. In order to obtain the independent scattering contributions of each SC, the geometrical modeling of the target is incorporated in the process of the SC extraction. Through ranking and selecting the SCs of all partitions, the accuracy and efficiency of the scattering simulation can be balanced through using different numbers of SCs. Radar imaging simulations of a complex quadrotor are investigated to validate the proposed approach.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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