Chinese Journal of Aeronautics, (2016), 29(3): 772–778

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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High-precision RCS measurement of aircraft's weak scattering source

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Received 31 August 2015; revised 30 January 2016; accepted 28 February 2016
Available online 9 May 2016

KEYWORDS

Microwave imaging;
RCS measurement;
Reflectivity distribution;
Spectral transform;
Weak scattering source

Abstract The radar cross section (RCS) of weak scattering source on the surface of an aircraft is usually less than −40 dBsm. How to accurately measure the RCS characteristics of weak scattering source is a technical challenge for the aircraft's RCS measurement. This paper proposes separating and extracting the two-dimensional (2D) reflectivity distribution of the weak scattering source with the microwave imaging algorithm and spectral transform so as to enhance its measurement precision. Firstly, we performed the 2D microwave imaging of the target and then used the 2D gating function to separate and extract the reflectivity distribution of the weak scattering source. Secondly, we carried out the spectral transform of the reflectivity distribution and eventually obtained the RCS of the weak scattering source through calibration. The prototype experimental results and their analysis show that the measurement method is effective. The experiments on an aircraft's low-scattering conformal antenna verify that the measurement method can eliminate the clutter on the surface of aircraft. The precision of measuring a −40 dBsm target is 3–5 dB better than the existing RCS measurement methods. The measurement method can more accurately obtain the weak scattering source's RCS characteristics.
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1. Introduction

Both theoretical calculations and experimental measurements show that the aircraft's different positions consist of many local scattering sources in the high-frequency range.[1,2] The echoes of the local scattering sources form the total scattered field of a target. The scattered field produced by a weak scattering source is several orders of magnitude lower than that produced by a strong scattering source, and therefore can be well ignored in the normal design of an aircraft. However, the overall radar cross section (RCS) of a stealth aircraft is rather small. At this point, the contribution of the weak scattering source to the overall RCS increases greatly; in particular, its effect is very obvious under certain polarizations or attitude angles. For these reasons, the study of the RCS characteristics of weak scattering sources and their scattering mechanisms is of far-reaching importance for the design of a stealth aircraft.

The RCS measurement is one of the methods for obtaining the scattering characteristics of a target.[3] The measurement of

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2016.03.003
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a target can not only help us understand the basic scattering mechanism but also obtain massive characteristic data of the target. Its RCS value is ultimately determined by measurement results. When the order of magnitude of its RCS value is rather big, the requirements for measurement system and measurement method are rather low, and the rather accurate results can be obtained with the normal RCS measurement method.[4] But when the order of magnitude of the RCS value of the target to be measured is rather low, for example, measuring the target whose RCS value is −40 dBsm requires that the error is 2 dB and that the background noise level reaches −60 dBsm[5], the measurement environment in an anechoic chamber cannot satisfy such requirements. Thus, the precise measurement of a weak scattering source has higher requirements for measurement system and measurement method. To improve the measurement environment, Ref.[6] designed a low-scattering foam column, enabling the measurement background environment ranging from 1.5 to 40 GHz to reach −50 dBsm and providing support for weak scattering source measurement. Refs.[7,8] proposed two RCS measurement methods to separate background environment from target signals, being favorable for the precise measurement of a weak scattering source. But they are difficult to apply these methods to an aircraft's weak scattering source measurement. Because the background for weak scattering source study is rather sensitive, there are few papers in the open literature on the topic related to an aircraft. Refs.[9,10] explained the importance of this type of measurement data for an aircraft's electromagnetic characteristic control and prediction. Refs.[11,12] gave the measurement results on edge diffraction source and slit diffraction source, demonstrated that this type of target is installed on the low-detectable diamond components and emphasized that the pertinent measurement data are scarce. Refs.[13,14] designed different measurement models for slit target and step target and performed experimental studies. Refs.[15,16] proposed the methods of image editing reconstruction, which are used for removing the clutter of background. The image of background is subtracted from the image of target with background. However, it is difficult to eliminate the effect of background when the scattering of target is very low.

Because the weak scattering source mostly exists on the surface of an aircraft, the scattering from the airframe envelope is the major cause for measurement errors. However, the normal RCS measurement method cannot distinguish the RCS characteristics contributions made by the airframe envelope and weak scattering source. This paper proposes a method for extracting the weak scattering source reflectivity distribution on the surface of an aircraft through microwave imaging and reversely developing its RCS contributions. The method uses a turntable's 2D microwave imaging algorithm to separate and extract the weak scattering source reflectivity distribution on the airframe envelope and then uses the wave spectrum theory to transform the spatial distribution spectra, thus obtaining the weak scattering source's own RCS contributions after prototype comparison. The experiments verify that in a normal anechoic chamber, the error of measuring a standard sphere of −40 dBsm with the method is only 1 dB. After imaging several metal spheres, the image of one of the metal spheres is extracted and then its RCS is reversely developed and compared with that of the sphere directly measured, with the measurement error being less than 0.5 dB. Finally, a low-scattering conformal antenna is used to verify the measurement; the verification results indicate that the measurement accuracy is 3–5 dB better.

2. Measurement system construction and measurement method

2.1. Stepped-frequency wideband RCS measurement system

To obtain longitudinal high range resolution, we use the stepped-frequency wideband signal.[17] The signal is a continuous wave signal with changes in equal-interval frequency and usually transmitted and received with the vector network analyzer in an anechoic chamber. The measurement of a target is carried out by transmitting stepped-frequency signals, thus obtaining its frequency response, whose inverse fast Fourier transform (IFFT) produces the high resolution time domain response of the target. The measurement system construction is shown in Fig. 1.

The target to be measured is placed in the quiet zone of an anechoic chamber. The vector network analyzer transmits the stepped-frequency signal, which is amplified by a power amplifier and then transmitted and received by the wideband horn antenna. The measurement is carried out with the quasi-monostation mode. There are coupling signals between reception antenna and transmission antenna (about −20 dBsm at the X band). To minimize the influence of the coupling signals on measurement accuracy, we placed some wave-absorption materials between the two antennas during the measurement. The computer controls the rotational speed and sampling interval of the turntable through the network wire. While rotating, the turntable transmits a trigger signal to the vector network analyzer, which then starts to respectively measure the frequency domain data of the background environment, the target to be measured and the calibration body at the same initial angle. The intermediate frequency bandwidth of a vector network analyzer is set to be 1 kHz, and its dynamic range is around 100 dB.

2.2. Microwave imaging algorithm

The high resolution imaging in an anechoic chamber often uses a turntable mode.[18] The wideband signal transmission produces range resolution, while the cross range resolution is achieved by the turntable rotation. The microwave imaging algorithm is similar to the chromatograph imaging in medicine.[19] The data obtained with the measurement at a certain angle are used to reconstruct the projection of a target's reflectivity distributed on a plane. The relationship between field and image obtained with measurement is given in Eq. (1)[20]:

$$g(x,y)=\int_{\theta_{\min}}^{\theta_{\max}}\int_{k_{\min}}^{k_{\max}}k\mathrm{G}(k,\theta)\exp\left[\mathrm{j}2\pi k(y\cos\theta-x\sin\theta)\right]\mathrm{d}k\mathrm{d}\theta \tag{1}$$

where the *x*-*y* coordinate system is a set of coordinates fixed in a target, and its origin is at the centre of turntable and changes with the change in the target; $g(x,y)$ is the image of the target to be measured; k is the spatial frequency and θ is the azimuth angle.

Because the integral limit in Eq. (1) does not satisfy the IFFT conditions, the algorithm implementation needs to shift the k frequency to $k_{\min}$. If $B'=k_{\max}-k_{\min}$ and B' is the band-

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