Scattering Characteristics of an Electrically-Large Aircraft Object Illuminated by Bessel Vortex Beams

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\textbf{ABSTRACT} Based on the excellent and broad prospect of the vortex beams in military application, it is necessary to evaluate the scattering characteristics of classical Bessel beam upon a perfect electrical conductor (PEC) blunt cone model of aircraft structure. First, a Bessel beam is expanded by a series of plane wave spectra. Then, combining the physical optics (PO) method, the scattered field of the object fitted by facet elements can be calculated. The amplitude, phase, and orbital angular momentum (OAM) spectra of scattered field for different object attitudes are discussed in detail. The results show that the backward scattering still retains good OAM characteristics, and which are distorted with the increase of oblique angle. Besides, the backscattering radar cross section (BRCS) of aircraft are also calculated and analyzed, and the scattered results of degenerated zero-order Bessel beam and plane wave are compared to verify the correctness of the proposed theory. Compared with plane waves, object scattering of vortex beams provides a new degree of freedom, providing more information for object detection.

\textbf{INDEX TERMS} Orbital angular momentum (OAM), physical optics (PO), plane wave spectra, aircraft, backscattering radar cross section (BRCS).

I. INTRODUCTION

In recent years, vortex wave [1] has attracted more and more attentions because of its huge information carrying capacity and potential advantage in wireless communication system [2], [3]. In addition, vortex waves are also applied in radar imaging [4], [5], [6] and rotational Doppler detection [7]. At the same time, there are many reported approaches to generate vortex waves [8], [9], [10]. For circularly polarized (CP) incidence, the co- and cross-polarized output fields can be implemented functionally separately to construct phase-modulated metasurfaces[11] for generating the vortex wave. By introducing detour phase[12], the design of the dual-polarized vortex beam generators in metasurface and metagrating form was proposed. In order to realize the application of vortex wave in object recognition and radar detection as soon as possible, the interaction mechanism between vortex wave and object is urgently needed.

According to our investigation, most of the object scattering characteristics of vortex waves are concentrated in the optical band. In particular, some results are obtained by using the wave function expansion method for microparticle spherical objects [13], [14], [15], [16], [17]. In [13], the scattering of light beam with OAM is studied by the Mie
scattering theory. In [14], By utilizing the spherical harmonics partial wave series, the off-axial scattering of a Bessel beam by a rigid fixed sphere is presented. Besides, a FDTD solution [18] was used to realize the scattering characteristics of laser vortex beam by dielectric particles.

However, there are few studies on the interaction between vortex waves and electrically-large objects in microwave band. The high order Bessel vortex wave is scattered by several typical targets has been investigated by using the surface integral equation method [19]. The RCS and 3D directivity plots of the far-field scattering for a typical aircraft model were presented. A modified multilevel fast multipole algorithm (MLFMA) is presented [20] to analyze the OAM scattering from the electrically large object illuminated by a spiral parabolic antenna.

In [21], The backscattering of single and double spherical objects is obtained by experimental RCS measurement method. Following, the reflection and refraction of vortex waves on a flat plate are analyzed [22], whose result is not only from experiments but also from the spectral domain expansion theory. In [23], the vortex wave generated by the uniform circular array (UCA) irradiates the PEC sphere and PEC cone, and the backscattering is calculated by combining the Stratton-Chu equation. Regrettably, the above reports are limited to solving the simple object scattering. For arbitrary convex objects, there is a lack of a comprehensive and systematic scattering calculation method.

In this paper, we calculate the vortex scattering of a scale model for aircraft structure named ‘raging fire’. In order to calculate scattering by PO algorithm, the object is divided into a series of fitting triangular facet elements. For each element, the amplitude, phase, and polarization of incident Bessel beam is different. Therefore, Bessel beam should not be directly brought into PO integral for calculation. Consequently, the Bessel beam is expanded into a superposition of a series of plane waves, and PO is performed to each sub-plane-wave. Finally, the scattering of all decomposed sub-plane-wave on all facet elements are summed vectorially to obtain the final result.

II. CALCULATION METHOD

As illustrated in Fig. 1, a Bessel beam propagating along the +z axis illuminates an aircraft structure. The coordinate system of incident Bessel beam is represented by the o-xyz, and the o in the global coordinate system O-XYZ are (x0, y0, z0). The time harmonic factor exp(−iωt) is assumed for convenience.

A. INCIDENT BESSEL BEAM

Based on the vector angular spectrum decomposition (VASD), the incident electric field of Bessel beam at (x0, y0, z0) can be expressed as [16]

\[ \vec{E}^{inc}(x, y, z) = k^2 \int_{\beta = 0}^{\pi/2} \int_{\alpha = 0}^{2\pi} \hat{A}(\alpha, \beta) \exp(i k \beta \sin \alpha \sin \theta \cos(\beta - \phi)) \times \exp(i k \alpha \cos \alpha) \sin \alpha \cos \alpha d\alpha d\beta \]

(1)

where \( \hat{A}(\alpha, \beta) = A(\alpha, \beta) \hat{f}(\alpha, \beta) \), \( A(\alpha, \beta) \) and \( f(\alpha, \beta) \) are the scalar amplitude and polarization state respectively. The angles \( \alpha \) and \( \beta \) are defined as the elevation and azimuth angles in the beam coordination system.

\[ \hat{f}(\alpha, \beta) = a\hat{e}_x + b\hat{e}_y - \left( \frac{\sin \alpha \cos \beta}{\cos \alpha}a + \frac{\sin \alpha \sin \beta}{\cos \alpha}b \right)\hat{e}_z \]

(2)

In this paper, the Bessel beam is selected as examples to conduct the analysis. The scalar amplitude function of a Bessel beam with arbitrary integer order is

\[ A(\alpha, \beta) = \frac{\delta(\alpha - \alpha_0)}{\sin \alpha_0} e^{i l \beta} \]

(3)

where the parameter \( \delta \) represents the Dirac function, \( l \) denotes the integer order topological charge, and \( \alpha_0 \) is the half-cone angle.

B. PO METHOD

Fig. 2 shows the model diagram of the general convex object fitted by a series of facet elements under the irradiation of the decomposed sub-plane-wave. According to the Stratton-Chu equation, the scattered field at an external position of any triangular facet element \( j \)-th on the PEC scatters can be given

\[ \vec{E}_j' = \frac{i}{\omega \epsilon \cdot 4\pi} \int_{s'} \left[ \frac{3 - k^2 R^2 - i k R}{R^5} e^{ikR} \times (\hat{R} \times \vec{J}_s(r')) + 2 \vec{J}_s(r') \left( 1 - \frac{1}{R^3} e^{ikR} \right) ds' \right. \]

(4)
where
\[ \tilde{J}_j(r') = \begin{cases} 2\hat{n}_j \times \tilde{H}_j^i, & \text{illuminated regions} \\ 0, & \text{others} \end{cases} \]  
(5)

and \( E_j^i(r) = \hat{e}_j^i \cdot \tilde{E}_j^i(r) \) and \( E_j^i(r) = \hat{e}_j^i \cdot \tilde{E}_j^i(r) \) denote the incident electric field components on triangular facet element \( j \)-th in the directions of perpendicular polarization \( \hat{e}_j^\perp \) and parallel polarization \( \hat{e}_j^\parallel \). \( \tilde{E}_j^i(r) \) is the any exploded sub-plane-wave of incident electric field in (1). \( \hat{n}_j \) is the normal unit vector of the facet element \( j \)-th on object. \( \theta_i \) is the incident direction of each decomposed plane wave angular spectrum. Taking into account the transformation relationship of coordinate systems, substituting (1) and (5) into (4) and switching the order of integral operation can obtain the scattered field.

\[ \tilde{E}_{total}^s = k^2 \int \int N_S \tilde{E}_j^i \sin \alpha \cos \alpha d\alpha d\beta \]  
(7)

where \( N_S \) is the number of partitioned surface elements.

Finally, the far-field RCS of the Bessel beam can be defined as

\[ RCS = \lim_{R \to \infty} 4\pi R^2 \left| \frac{\tilde{E}_{total}^s}{\tilde{E}_{inc}} \right|^2 \]  
(8)

III. RESULTS AND ANALYSIS

In this section, numeric calculations are conducted to analyze and evaluate the backward scattered field and BRCS for aircraft object that is divided into 20002 triangular facet elements with side length of 0.3\( \lambda \) (\( \lambda \) is 300mm). Assuming that the \( x \)-polarized Bessel beam \((a = 1, b = 0)\) is incident in the head of the aircraft, the observation cross section is 40\( \lambda \times 40\lambda \), and the tail of the aircraft coincides with \( z = 0 \) plane.

A. BACKWARD SCATTERING RESULT

Fig. 3 depicts the amplitude and phase cross section distributions of the backward scattering varying with the scattering distance. This clearly shows that the backward scattered field still maintains good OAM characteristic maybe due to the symmetrical object. In the cases of both topological charge \( l = 1 \) and \( l = 2 \), amplitude hollow and helical phase wavefront characteristics are presented, and the Bessel wave can generate diffusion and attenuation as the scattering distance increases. In addition, compared with \( l = 1 \), the amplitude hollow becomes larger and the magnitude decreases in the case of \( l = 2 \), which is consistent with the characteristics of incident Bessel beam.

In order to further analyze the OAM modal purity of the back echo, Fig. 4 presents the normalized scattered OAM spectra distributions under the incident Bessel beam with different topological charge. It can be seen that all scattering OAM spectra obtain a high modal distribution under the incident Bessel beam. For a blunt cone aircraft object with symmetric prototype, the backward scattered amplitude and phase distributions under different degrees of deviation from the vertical incident direction are illustrated in Fig. 5. The relative position relationships are indicated in the diagram. With the increase of oblique incidence angle, the backward scattered Bessel wave will produce some distortion, which is manifested in the gradual loss of hollow amplitude and spiral phase wavefront respectively. When the oblique angle is
When the oblique angle exceeds $2^\circ$, the Bessel wave loses the helical wavefront and the amplitude distribution becomes conical shape gradually.

Finally, Fig. 6 shows the normalized OAM spectra distributions at different tilt angles $\alpha$. The proportion of the hybrid modes is enhanced with the increase of the tilt angle, which corresponds to the distortion of the backward Bessel scattered waves. Regardless of $l = 1$ or 2, the highest proportion of the hybrid mode reaches about 60% when the oblique incidence angle is $2^\circ$, which is mutually confirmed with the loss of OAM characteristics of the scattered field under the corresponding case in Fig. 5.

### B. BRCS OF THE AIRCRAFT

In this section, the backscattering characteristics of aircraft are mainly discussed. Fig. 7 is a schematic diagram of the aircraft’s backscattering of Bessel radar. The Bessel radar scans clockwise from the head ($\theta = 0^\circ$) to the tail ($\theta = 180^\circ$) of the aircraft. Similarly, the far-region scattered field of a PEC object can be obtained by PO integral as follows

$$E_s = -\frac{ik^2}{2\pi\omega\mu} \frac{\exp(ikr)}{r} \int s_1 \hat{R} \times [\hat{R} \times (\hat{n} \times H')] \times \exp(-ik\hat{R} \cdot \hat{r}') ds'$$

where the incident field is in the opposite direction to that of the scattered field.

To verify the correctness of aircraft scattering calculated by the proposed method for Bessel wave, the object is illuminated by the degraded Bessel beam ($l = 0^\circ, \alpha_0 = 0^\circ$) and plane wave, respectively. As shown in Fig. 8, the peak value of BRCS of both the plane wave and the zero-order Bessel beam appear at the tail ($\theta = 180^\circ$), which can be interpreted as a circular planar structure with a high RCS at the tail. When $\theta = 90^\circ$, the zero depth of BRCS occurs maybe due to the discontinuities between the cone and cylinder in this aircraft structure. The BRCS curves from the illumination of the above two types of incident wave coincide well, which effectively verifies the proposed theoretical method and program code. Some subtle differences may be due to the numerical algorithm errors and facet element precision.

Fig. 9 shows the BRCS curves of aircraft under Bessel beam irradiation with different topological charges and different half-cone angles. Fig. 9.(a) shows that the backscattering curves of Bessel beam with different topological charges have few differences. Compared with plane wave’s irradiation, zero depth appear at both $\theta = 0^\circ$ and $\theta = 180^\circ$, which is
the most significant target characteristic difference between plane wave and Bessel wave. As can be seen from Fig. 9. (b), with the increase of the half-cone angle, the BRCS level of Bessel wave decreases, while the central deviation occurs at all the three strong scattering positions of $\theta = 0^\circ$, $\theta = 90^\circ$, and $\theta = 180^\circ$. The BRCS variation of Bessel beam with different half-cone angle also provides an additional recognition information for the object, which further enhances the accuracy and reliability of object recognition.

Although the BRCS curves with different topological charges have few differences as shown in Fig. 9. (a), the fast Fourier transform (FFT) corresponding to different OAM states can obtain more abundant information in azimuth angle. Therefore, by using Bessel wave to replace plane wave in synthetic aperture radar (SAR) imaging algorithm, a good transverse resolution can be obtained [24]:

$$\rho_a = \frac{\lambda}{2\theta_{BW}}$$

where $\rho_a$ is the azimuth resolution, $\lambda$ is the wavelength, and $\theta_{BW}$ is the effective azimuth beam width. For circular array with the same antenna aperture size, vortex wave and ordinary electromagnetic wave can be generated respectively with or without phase delay. The azimuth beamwidth of the far field pattern of vortex wave is larger than that of traditional electromagnetic wave evidently. Therefore, higher azimuth resolution of OAM imaging can be obtained according to (9).

Fig. 10 presents the BRCS of Bessel beams with different incident wavelengths, and the result shows that the curve fluctuation becomes more obvious with the decrease of wavelength. Importantly, this numerical method has a strong universality and can be applied to the acquisition of electrically-large object characteristics in the terahertz or even optical frequency band.

IV. CONCLUSION

This paper investigates the interaction mechanism between Bessel beam and a blunt cone aircraft object. The combination of angular spectra expansion and facet segmentation method makes the object scattering characteristic of Bessel waves not limited to simple structures. The distribution of backward scattered fields and OAM spectra obtained from different object attitudes reveal that the OAM characteristics of Bessel vortex wave echo from symmetric object are better than those from asymmetric object. The backscattering results show that the strong scattering points of the aircraft object include head, side and tail. There is no significant difference in the BRCS of Bessel beam with different topological charges. However, the BRCS phenomenon under different half-cone angle at the main scattering positions is similar to the characteristics of incident Bessel wave: with the increase of the half-cone angle, the amplitude decreases and the main lobe shifts away from the zero depth. This study has great
potential significance for future military radar and Bessel vortex object recognition.

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