Influence evaluation of UAV inlet on electromagnetic scattering and time-frequency characteristics

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Abstract. An analytical method for electromagnetic scattering characteristics of complex unmanned aerial vehicle targets by using hybrid multilevel fast multipole algorithm (MLFMA)-physical optics (PO) and short-time fourier transformation (STFT) is proposed in this paper. By constructing accurate electromagnetic models of unmanned aerial vehicle (UAV) target with inlet, the aspect and polarization characteristics of radar cross section (RCS) and time-frequency representation (TFR) are studied. To validate the influence of the inlet, the monostatic and bistatic RCS at specific angles, RCS statistical characteristics and TFR correlation are simulated and compared. It is concluded that the inlet should be sufficiently considered to calculate the accurate scattering characteristics.

1. Introduction
With the continuous development of stealth and target recognition technologies, the electromagnetic scattering of electrically large complex targets with cavities becomes more and more important in practical radar technologies, such as radar cross section (RCS) calculation of aircraft inlets, engines and other components [1]. The inlet is one of the strong scattering components of the aircraft, which has a great contribution to the RCS of the aircraft head. The shape and size of the cavity will affect the scattering of electromagnetic waves. In general, there are many geometric factors that affect the electromagnetic scattering of the cavity, including aperture shape, cavity depth, cavity inner wall shape, and cavity sub-scatterers. In order to achieve the purpose of radar cross-section reduction, the inlets of military aircrafts are mostly designed as S-shaped curved variable cross-section shapes.

Since this kind of electrically large size involves multiple reflections, edge diffraction and other issues, it is difficult to guarantee the reliability of the calculation results using the high-frequency approximation method alone. At present, the effective solution is to combine the approximation method with the full-wave method according to the specific structural characteristics. However, these are all researches on the cavity at the computational level [2-3].

In the high frequency region, the scattering field of radar target can be approximated as the result of superposition of multiple independent strong scattering sources, which are called scattering centers [4]. The scattering characteristics of radar targets are determined by the properties of their scattering centers, and the properties of scattering centers depend on the radar azimuth, frequency and polarization characteristics [5]. Time-frequency representation (TFR) can be used to separate the scattering centers in the time domain and obtain corresponding relationship between them and their time-frequency signature, which further provides support for geometric feature and motion feature extraction and target recognition [6]. The STFT algorithm is simple and facilitates the understanding of image features, so the following theoretical analysis uses this algorithm.
In this article, complex electromagnetic models for typical airplane, such as unmanned aerial vehicle (UAV) are constructed, including nose, fuselage, wings, tails and inlet. The inlet model is designed as S-shaped curved variable cross-section shapes. Through calculation and comparison of electromagnetic signature of RCS and TFRs, the effect of different structures is studied. The influence of characteristics provides an effective basis for the construction of the electromagnetic characteristics database of UAV and inlet target.

2. Modeling of UAV

The model in this paper is based on UAV. The accuracy and reliability of the calculated RCS depend on the accuracy of the three-dimensional electromagnetic model of the UAV. In order to improve the accuracy of the model, the surface curvature and structural detail must be reflected in the model as much as possible. In this paper, accurate and usable models for UAV target are built and meshed.

In order to analyze the effects of air inlet on the scattering characteristics for UAV targets, typical models are established. The geometric structures are shown in figure 1. The model consists of nose, fuselage, wings, tails and junctions between them. In model A, the engine inlet of UAV model is closed, and in model B the inlet modelled open-ended cavity is included to obtain more accurate RCS.

The geometric parameters are set as follows: the fuselage of the aircraft is 6m, the wingspan is 9m, and the thickness of the wing is 0.25m. The schematic diagram of the inlet is shown in figure 2. It can be seen that the cross section of the intake port gradually transitions from a half-moon shape to a circular shape. To study the scattering of airplanes with air inlets, the electromagnetic scattering calculations are carried out by combining the air inlets mounted on the fighter jets and the outer surface of the airplane as a whole.

It should be noted that the external surface of the aircraft and internal surface of the inlet are represented as the perfect electric conductor (PEC), and the interior details, such as an engine is omitted to reduce overall computational cost at the expense of degraded accuracy.
3. Electromagnetic Scattering Analysis

3.1. Signature of RCS
The UAV model mentioned in figure 1 is on the $xo\ z$-plane. The cockpit is located towards the $+z$ direction, and the main wings are located along the $±x$ direction. In order to study the polarization and aspect characteristics of different models, the RCS is calculated by hybrid MLFMA-PO algorithm and given for comparison.

EM parameters are set as follow: the frequency of the incident plane wave is 1 GHz, and the incident angles are $\varphi = 0^\circ$ and $\theta = 0^\circ \sim 360^\circ$ with step of $0.15^\circ$ in $xo\ z$-plane. The co-polarization comparison results for monostatic and bistatic RCS are respectively shown in figure 3 and figure 4.

![Figure 3](image1.png)  
Figure 3. Monostatic RCS of UAV for co-polarization. (a) VV. (b) HH.

![Figure 4](image2.png)  
Figure 4. Bistatic RCS of UAV for co-polarization. (a) VV. (b) HH

From the full-angle results in figure 4, it can be seen that there are peaks at some angles ($\theta = 35^\circ, 58^\circ, 145.65^\circ$) where monostatic RCS is over 10dB. The results show that there are scattering centers formed by the reflection waveform of a plane, a single curved surface, or a straight edge in these directions, especially related to the fuselage, wings and tail. The maximum RCS is $14.82\text{dB}$ at $\theta = 145.65^\circ$ for VV polarization and $13.96\text{dB}$ at $\theta = 57.75^\circ$ for HH polarization. From compared results in figure 4 and figure 5, it can be seen that the effect is mainly concentrated at entrance of the air inlet, which causes the RCS to increase within about $±30^\circ$ angles interval around $\theta = 0^\circ$, up to $37.7\text{dB}/45.8\text{dB}$ for monostatic VV/HH RCS and $38.8\text{dB}/43.6\text{dB}$ for bistatic VV/HH RCS.
The root mean square error (RMSE) for compared RCS results is illustrated in table 1. All the RMSE values are greater than 7dB. In order to describe the influence at different angles, the local RMSE is shown in figure 5, which represents the RMSE of the two groups of data from 0 to this angle. As shown in Figure 5, it is verified that the influence around UAV nose is larger, and the influence on VV is greater than that on HH in \( \theta \in [0,13.5^\circ] \), otherwise b is greater than a. The maximum RMSE on V polarization is at \( \theta = 9^\circ \), the effect gradually decreases to less than 20dB after \( \theta > 20^\circ \). The result shows that the RCS of UAV is greatly affected by the air inlet, especially around nose direction.

Table 1. RMSE of RCS results between models

| Polarization | Monostatic RCS | Bisatic RCS |
|--------------|----------------|-------------|
| VV           | 7.6514         | 7.9281      |
| HH           | 9.5678         | 11.3752     |
| VH           | 8.6582         | 15.7755     |
| HV           | 8.3175         | 10.5772     |

3.2. Signature of TFR

In this section, the TFRs of the scattered waves are simulated and analyzed. The signatures shown in TFR represent the Doppler frequencies and scattering amplitudes of scattering centers. The scattering centers of extended targets can be divided into three types [7]: local scattering centers (LSC), distributed scattering centers (DSC) and sliding scattering centers (SSC). LSC is the scattering center formed by the sharp diffraction of planar or cubic vertices. DSC is the scattering center formed by the reflection wave of the plane, single surface or straight edge. SSC is the scattering center formed by the smooth surface or smooth curved edge. According to the formation mechanism of three kinds of scattering centers, it can be seen that the scattering centers of cavity targets mainly include LSC formed by apex diffraction, SSC formed by smooth curved edge diffraction, DSC formed by single surface primary reflection and DSC formed by multiple reflections in the cavity. In order to distinguish, the scattering center formed by cavity is marked as cavity scattering centers (CSC). Doppler frequencies are closely related with the locations of scattering centers. The geometry and all the possible LSCs, DSCs, and SSCs of the UAV is shown in figure 6.

The results of TFRs based monostatic RCS using STFT are compared in figure 7-8. It is shown that located scattering centers are distributed induced by reflected waves, are shown as individual bright blocks flashed at discrete angles. It is obvious that the existence of the air inlet makes the time-frequency image appear obvious bright areas in a large area of the nose.

![Figure 5. RMSE of RCS](image1)

![Figure 6. Scattering centers of the UAV.](image2)
Through the comparison of TFRs difference between two models, the influence of inlet on the amplitude and position of the scattering centers at certain angles is confirmed. The correlation coefficients (Corr-Coefs) between the extracted Doppler frequencies between different models under vertically and horizontally polarization are given in table 2.

![Figure 7. TFRs processed by STFT of monostatic RCS at VV. (a) UAV (b) UAV with inlet](image)

![Figure 8. TFRs processed by STFT of monostatic RCS at HH. (a) UAV (b) UAV with inlet](image)

![Figure 9. TFRs processed by STFT of bistatic RCS at VV. (a) UAV (b) UAV with inlet](image)

![Figure 10. TFRs processed by STFT of bistatic RCS at HH. (a) UAV (b) UAV with inlet](image)
The results of TFRs based bistatic RCS data are compared in figure 9-10. Through the comparison of TFR results in figure 9-10, the presence of the inlet also has a great influence on the bistatic characteristics in a wide range around the nose.

From table 2, it can be seen that the Corr-Coefs of monostatic TFR are under 88% for co-polarization and less than 78% for cross-polarization. In the case of the same polarization, the Corr-Coef of bistatic is higher than that of monostatic.

Table 2. Corr-Coefs(%) of TFR results between models

| RMSE(dB)   | Monostatic TFR | Bistatic TFR |
|------------|----------------|--------------|
| VV         | 87.1%          | 92.82%       |
| HH         | 79.69%         | 85.28%       |
| VH         | 54.47%         | 77.61%       |
| HV         | 77.18%         | 82.14%       |

4. Conclusion

Aiming at the electromagnetic scattering problem of complex airplane targets, the aspect and polarization characteristics of RCS and TFR are analyzed in this paper. In order to study the effects of air inlet on their scattering characteristics, hybrid MLFMA-PO is used to accomplish RCS calculation for the established UAV models. The simulation analysis results show that the RCS at certain angles range increases greater than 40 dB, and the RMSE of all polarization is greater than 7.5dB. Moreover, the correlation coefficients of mono/bi-TFRs for full polarization are less than 90% except for the case about bi-VV, which confirms that the influence of the inlet on the echo characteristics should be sufficiently considered. The research in this paper provides a theoretical basis for the accurate analysis of UAV with inlet scattering characteristics.

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