Approach of Electromagnetic modeling for chaff clouds formed by exploding

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***Abstract*—As a typical and effective passive jamming, chaff has been widely used in electromagnetic countermeasures. The chaff cloud formed by the explosion of chaff bomb is one of the main ways to realize the self-defense interference of the aircraft and the ship target. Aiming at the two stages of chaff cloud formation process in this delivery mode: rapid dispersion stage and stable diffusion stage, the electromagnetic modeling method is studied. Firstly, the diffusion process and spatial distribution of chaff in the atmosphere are analyzed according to aerodynamics and stochastic theory; Then, the electromagnetic scattering calculation method of chaff clouds at two stages is derived respectively by using absorption theory and dipole radiation theory; Finally, the space varying RCS curve and the time varying RCS curve of chaff cloud are given by modeling and simulation. The simulation results are analyzed and some meaningful conclusions are obtained.**

Keywords—chaff clouds; diffusion characteristics; Radar Cross Section

I. INTRODUCTION

Chaff finds its main applications in electromagnetic countermeasures. A cloud of chaff is a diffuse artificial target made up of half-wave dipoles. Different chaff dispensing methods allow its use for various types of mission which include deception, distraction, seduction, confusion or screening and so on[1]. The study of electromagnetic scattering by a chaff cloud is so complex that no exact theory is currently available for well describing all the phenomena observed. That is because chaff RCS depends on many parameters like physical characteristics of the dipoles, their packaging, their aerodynamic behavior as well as atmospheric and dispersion conditions.

In order to address such situations, a novel Approach of Electromagnetic modeling for chaff clouds formed by exploding proposed. Section 2 describes the basic aerodynamic model of chaff clouds and its space distribution model, while Section 3 describes the Approach of Electromagnetic computational method. Simulation results are presented and discussed in section 4. Finally, some significant conclusions are summarized in last section.

II. AERODYNAMICS AND SPACE DISTRIBUTION

The motion of chaff cloud consists of the whole motion and the motion between chaff and its rotation. These motion characteristics make the amplitude and phase of chaff scattering signal change with time. Chaff clouds formed after explosion of chaff bombs can be divided into two stages: rapid dispersal stage and stable diffusion stage. The first stage is the chaff cloud before the formation of effective interference, during this time the chaff velocity attenuation is very fast, generally within one second, from tens of meters per second attenuation to less than one meters per second. The second stage is the effective interference of chaff clouds, at which time the velocity of chaff is determined by the inherent attributes of chaff and the wind speed of the environment.

In the first stage, the equation of motion of chaff is as follows[2],

$$V(t) = V_0 / (1 - cV_0 t)\ , 0 \le t \le T \tag{1}$$

$$L = -In(1 - cV_0 t) / c\ , 0 \le t \le T \tag{2}$$

Where, $V(t)$ is the velocity of chaff; L is the migration length of chaff; V_0 is Initial velocity of chaff obtained from chaff bomb explosion; c is empirical constant and T is dispersal time of chaff clouds.

When chaff cloud reaches a steady state, namely second stages, Supposed that the spacing between chaff is greater than two times the radar wavelength, and chaff does not collide with each other, the motion of each chaff is only determined by its initial state and ambient wind speed. The motion of chaff cloud is represented by the group effect of a large number of independent chaff motion[3].

The chaff moving in the dense atmosphere is affected by gravity, air resistance and air buoyancy simultaneously. Assuming the shape of chaff is a slender cylinder, a global coordinate system is established in the vertical plane as shown in figure 1. Suppose the angle between chaff and Z axis is θ, at steady state, the descending velocity is v, horizontal velocity is u ,then the horizontal velocity is located in the plane formed of chaff direction and plumb line.

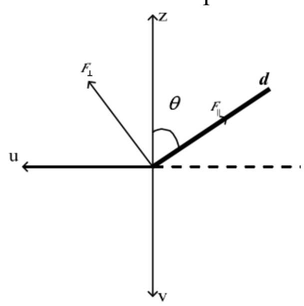


Fig. 1. Sketch map of chaff dynamics analysis

According to the theory of low Reynolds number in aerodynamics, the formula of motion can be deduced[4],

$$u = \frac{g\Delta\rho r^2}{4\mu}\sin\theta\cos\theta\left[In(\frac{L}{r}) - \frac{3}{2}\right] \quad (3)$$

$$v = \frac{g\Delta\rho r^2}{4\mu}\left\{\left[In(\frac{L}{r}) - \frac{3}{2}\right]\cos^2\theta + \left[In(\frac{L}{r}) + \frac{1}{2}\right]\right\} \quad (4)$$

Where, L is the length of chaff, r is the radius of chaff, μ is the coefficient of viscosity where chaff at altitude, $\Delta\rho$ is the difference of density between chaff and air, g is the acceleration of gravity, $\pi l r^2 \Delta\rho g$ is the resultant force of chaff gravity and air buoyancy.

In addition to the translational motion, the chaff also has rotational motion. In the process of chaff descent, it is assumed that the rotational angular velocity and rotation axis remain unchanged. Suppose the chaff orientation is $\hat{\mathbf{d}}$; the unit vector of the rotation axis is $\hat{\mathbf{d}}_w$. After the time t, the rotation angle is $\Delta\theta = wt$. The orientation of the chaff after rotation is as follows,

$$\hat{\mathbf{d}}_{new}{}^{T} = \mathbf{T}(\hat{\mathbf{d}}_w, t)\hat{\mathbf{d}}^T \quad (5)$$

Where, $\mathbf{T}(\hat{\mathbf{d}}_w, t)$ is the rotation transformation matrix.

The chaff cloud formed after the explosion of the chaff bomb is approximately a spheroid. Before the steady state of chaff cloud is reached, if the maximum diffusion velocity is V_A, dispersal time is t_A, then the chaff cloud is centered on the position of the explosion time of the chaff bomb, and a spherical steady state is formed with the radius $R_A = V_A t_A$ of dispersion, and the density distribution of chaff obeys the three-dimensional Gauss distribution.

Similarly, the chaff pointing distribution in chaff clouds has a great influence on the radar scattering characteristics of chaff clouds. Assuming that the chaff cloud reaches steady state, the direction of the chaff obeys the uniform spherical distribution.

The chaff rotation in chaff clouds also affects the radar scattering characteristics of chaff clouds. It is assumed that the rotation axis of each chaff in the chaff cloud obeys the uniform spherical distribution, and the rotation speed obeys the zero mean Gauss distribution, and the rotation speed and rotation axis of each chaff are unchanged.

III. ELECTROMAGNETIC CALCULATION

Theory and practice have proved that the electromagnetic scattering problem of slender chaff can be equivalent to the radiation problem of symmetric dipole antenna[5]. Suppose that chaff is made of straight wires with radius *a* and length 2*l*. By deducing, the chaff scattering field can be expressed as[6],

$$\vec{\mathbf{E}}_{sc} = \begin{bmatrix} E_{h2} \\ E_{v2} \end{bmatrix} = -j\frac{e^{-jkr}}{kr}\frac{\eta L}{z_0\lambda}\frac{\cos(kl\cos\theta) - \cos(kl)}{\sin\theta}\cdot \begin{bmatrix} \cos^2\alpha & \cos\alpha\sin\alpha \\ \cos\alpha\sin\alpha & \sin^2\alpha \end{bmatrix}\begin{bmatrix} E_{h1} \\ E_{v1} \end{bmatrix} \quad (11)$$

Where, α is the azimuth of chaff orientation in polar coordinate system.

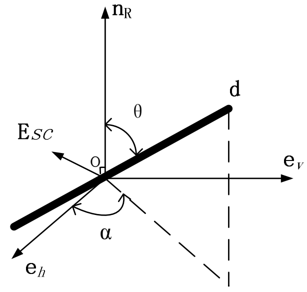


Fig. 2. Sketch of chaff scattering in polar coordinate system

According to the polarization relation of scattering field, the output signal of the far zone receiver will be proportional to the scattered field component along the polarization direction of the receiver, so we could redefine RCS as follow,

$$\sigma_s = \lim_{R\to\infty} 2\sqrt{\pi}R\frac{\mathbf{E}_s \cdot \hat{\mathbf{e}}_r}{E_0}e^{-jkR} \quad (12)$$

Where, $\hat{\mathbf{e}}_r$ is the electromagnetic polarization direction vector of receiver, R is the distance from the target to the radar receiver; $\mathbf{E}_s$ is the Scattering field of target; E_0 is the electric field intensity of incident wave.

Chaff clouds have mutual coupling effect before they are dispersed, which mainly include occlusion effect, blocking effect and screening effect. Due to the existence of mutual coupling effect, chaff cannot exert its jamming efficiency. Research shows when the distance between chaff is greater than two times of the radar wavelength, these effects can be ignored. The classical absorption theory gives the radar cross section expression of chaff cloud before charging and dispersing as follows[7],

$$\sigma = S_c(1 - e^{-N\sigma_0}) \quad (13)$$

Where, S_c is the projected area of chaff cloud perpendicular to radar line of sight and illuminated by beam, N is the number of chaff per unit area in projected area of chaff cloud, σ_0 is the average radar cross section of a chaff without considering mutual coupling effect (For half wavelength chaff, $\sigma_0 = 0.153\lambda^2$).

After the chaff is completely dispersed, the distance between each chaff meets the condition of more than two times of the wavelength, then the radar cross section of chaff cloud can be expressed as,

$$\sigma = \sum_{n=1}^{N} \sigma_i \quad (14)$$

Where, N is the total number of chaff, σ_i is the radar cross section of chaff at i.

IV. SIMULATION RESULTS

Suppose a chaff bomb contains one million chaff numbers, each chaff length is 1.5cm, launched and exploding in 6km, the ambient wind speed is 0.2m/s and its direction is horizontal and the angle is 45 degrees with the X axis. After 0.5 seconds, the steady state of the chaff cloud is reached. Figure 3 shows the motion process of this chaff cloud. It can be seen from the diagram that the overall motion of chaff cloud is affected by the ambient wind speed, and the diffusion motion of chaff cloud is mainly affected by the characteristics and direction of each chaff.

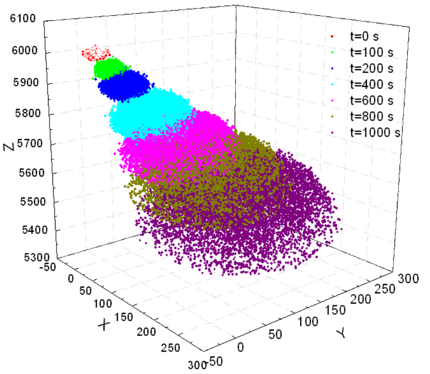


Fig. 3. Fig 3 Diffusion process of chaff cloud

When the chaff cloud reaches steady state after explosion, In figure 4, the curve of the change of RCS with the incident angle of electromagnetic wave at three polarization conditions is given when the radar frequency is 10GHz, and the incident azimuth is zero degrees. Statistical analysis shows that the RCS mean value of HH polarization is 19.46dB, and VV polarization is 22.13dB, HV polarization is 14.61dB. The theoretical value of RCS with the same polarization is 21.58dB, while the theoretical value of cross polarization RCS is 16.83dB, which is consistent with the simulation modeling results.

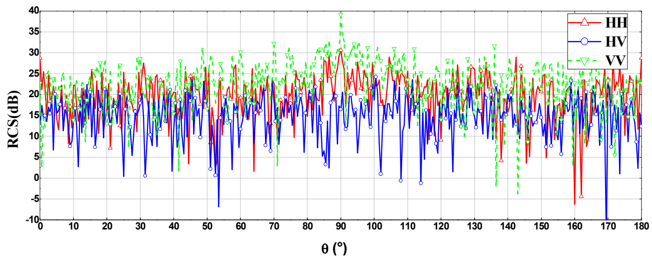


Fig. 4. Variation curve of RCS with elevation of chaff cloud

Figure 5 gives the time varying curve of RCS when the chaff cloud reaches steady state. Within 100 seconds after the steady state is reached, the azimuth angle of the electromagnetic wave is zero degrees, the pitch angle is 150 degrees, and the frequency is 10GHz. Statistical analysis shows that the RCS mean value of HH polarization is 18.02dB, and VV polarization is 19.71dB, HV polarization is 14.07dB. It can be seen from the diagram that with the continuous diffusion of chaff clouds, the radar cross section of chaff clouds will not decrease as long as the chaff is still in the radar beam range.

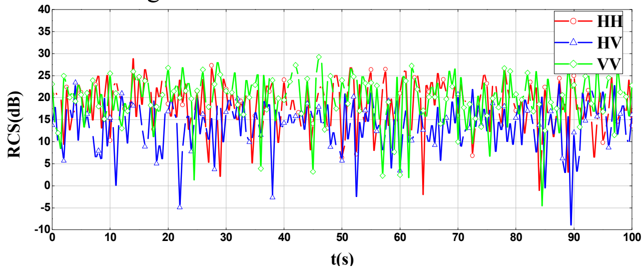
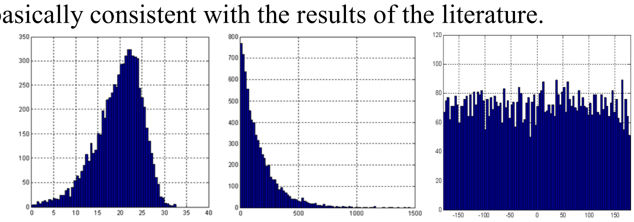


Fig. 5. Time varying RCS curves of chaff clouds

The statistical results of RCS amplitude and phase of chaff cloud under HH polarization are given in figure 6(a), figure 6(b) and figure 6(c) respectively. It can be seen from the diagram that the logarithmic RCS amplitude obeys the Gauss distribution approximately, while the linear RCS amplitude obeys the exponential distribution, and the phase of RCS obeys the uniform distribution. The simulation results are basically consistent with the results of the literature.



(a) logarithmic value of RCS (b) linear value of RCS (c)phase of RCS

Fig. 6. Histogram statistics results of chaff cloud RCS amplitude and phase

V. CONCLUSIONS

This paper presents an electromagnetic modeling method for chaff clouds formed by chaff explosion. Numerical results verify the effectiveness of the proposed method. By using the method of chaff cloud modeling needs some ideal prior conditions, such as neglecting the mutual collision between each other, spatial distribution and point distribution, ignoring air turbulence, while these prior conditions have certain differences in the practical application of the chaff. In more elaborate modeling, these situations need to be further studied.

REFERENCES

[1] Chen J, Principles of Radar Chaff Jamming [M], National Defense Industry published, May 2007.

[2] James Brunk, et al. Chaff Aerodynamics. Alpha research, Prepared for Air Force Avionics Laboratory, November 1975.

[3] Dong W. S, Hyun-Jae N, et al. Dynamic RCS estimation of chaff clouds [J]. *IEEE Trans on Aerospace and Electronic Systems*, Vol.48 No.3 July 2012.

[4] Sherman W. Marcus. Dynamics and radar cross section density of chaff clouds [J]. *IEEE Trans on AES*, 2004, 40(1):93-102.

[5] Kai Fong Lee. Principles of Antenna Theory [M]. The Chinese University of Hong Kong, John Wiley and Sons,1984:44-46.

[6] Li Jin-liang, Wang Xue-song, et al. Polarization characteristics of Gaussian oriented chaff clouds[J]. *Chinese Journal of Radio Science*, Vol.23, No.3 June, 2008.

[7] Kownacki S. Screening effect of a chaff cloud [J]. *IEEE Trans on AES*, July, 1967(4):731-734.