Influence of plasma sheath on radiation characteristics of antenna based on ray tracing method

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***Abstract*—Accroding to the existing non-uniform plasma sheath flow field data, the flow field was segmented. the influence of the plasma sheath at different heights, velocities, and angles of attack on the radiation pattern of the antenna electric field was studied applying a ray tracing method. The results show that the higher the speed of the hypersonic vehicle is, the more serious the attenuation of the electric field of the antenna is. When the speed reaches Mach 25, the electric field is almost completely attenuated to zero.After exceed the height of 30 km, the electric field decays more with the increase of height. Furthermore, the attenuation of the electric field in the two half planes of xoy and yoz planes is difference with the change of angle of attack.**

Keywords—plasma sheath; ray tracing; pattern; height; velocity; attack angle

I. INTRODUCTION

When a hypersonic vehicle is flying in the atmosphere, plasma sheath is generated on the surface of the aircraft due to the shock and the high temperature and high pressure that ionize the dense air around the aircraft [1][2]. This phenomenon will affect the radiation characteristics of antennas placed on the aircraft, such as communication with the outside world and remote sensing antenna. In severe cases, even the shielding of electromagnetic signals will cause "blackout", which will result in interruption of communication between the aircraft and land, loss of detection targets and so on. Therefore, the study of plasma sheath on the antenna is worthwhile work.

In the study of the influence of plasma sheath on the antenna, foreign researchers started their work earlier. JMHamm and G.Tyar used the plasma sheath simulation technology to study the effects of various types of sheath discontinuities and inhomogeneities on the aperture antenna radiation Figure and the effect of input impedance [3]. Peking University Wang Wenqing conducted an experimental study on the radiation performance of a 660-760 mm longwave half-wave antenna surrounded by artificial plasma and the attenuation of field strength after the electric wave passes through the plasma [4]. Zhan Dawei presented the layout scheme of altimeter antenna and GPS antenna on X-37B spacecraft and analyzed the influence of temperature and plasma sheath on the radiation characteristics of the antenna under the variation of flight dynamic parameters [5]. Traditional research methods have been very mature in the study of the impact of plasma sheath on the antenna. However, most studies use the ideal layered plasma sheath which couldn't reflect the plasma distribution under real conditions.

In this paper, we studied the change of the electric field when the electromagnetic wave propagating in the plasma sheath based on ray tracing. and obtained the electric field radiation patterns of two orthogonal planes. This work can provide a certain reference value for hypersonic aircraft antenna placement and direction to improve communication quality.

II. ELECTROMAGNETIC WAVE PROPAGATION LOSS IN PLASMA

Plane electromagnetic wave is the basic solution of Maxwell's equations.Taking into account the effective collisions of electrons and neutrals, the exponential function of electromagnetic wave is as follows: $\exp j(\omega t\text{-}\boldsymbol{k}\bullet\boldsymbol{r})$ .The decay constant α and phase constant β are calculated as follows [6]:

$$\alpha=\frac{\omega}{c}\left\{\frac{1}{2}\left[-\left(1-\frac{{\omega_p}^2}{\omega^2+{\nu_c}^2}\right)+\sqrt{\left(1-\frac{{\omega_p}^2}{\omega^2+{\nu_c}^2}\right)^2+\left(\frac{\nu_c}{\omega}\frac{{\omega_p}^2}{\omega^2+{\nu_c}^2}\right)^2}\right]\right\}^{1/2} \quad (1)$$

$$\beta=\frac{\omega}{c}\left\{\frac{1}{2}\left[\left(1-\frac{{\omega_p}^2}{\omega^2+{\nu_c}^2}\right)+\sqrt{\left(1-\frac{{\omega_p}^2}{\omega^2+{\nu_c}^2}\right)^2+\left(\frac{\nu}{\omega}\frac{{\omega_p}^2}{\omega^2+{\nu_c}^2}\right)^2}\right]\right\}^{1/2} \quad (2)$$

Where ω_p is the plasma frequency, ω is antenna and ν_c is collisions frequency.If $\vec{r}$ and $\vec{l}$ in the same direction, then after the electromagnetic wave has passed the distance r, the electric field becomes [7]:

$$E = E_0 \exp(-\alpha r)\exp[j(\omega t - \beta r)] \tag{3}$$

III. Ray Tracing Algorithm in Non - Uniform Plasma Sheath

Ray tracing method mainly deals with two aspects including: ray path search and ray field calculation. The ray tracing search mainly calculates the refraction angle inline with the incident direction of the electromagnetic wave and the dielectric constant of the upper and lower layers, and then obtains the propagation path of the electromagnetic wave. The calculation of the ray electric field intensity includes the calculation of the electric field intensity of the reflected ray and the intensity of the transmission field strength.

For layered media, the ray traces are only related to the direction of incidence and the dielectric constant of the layers. Route trajectory between the layered dielectric layer shown in Figure 1:

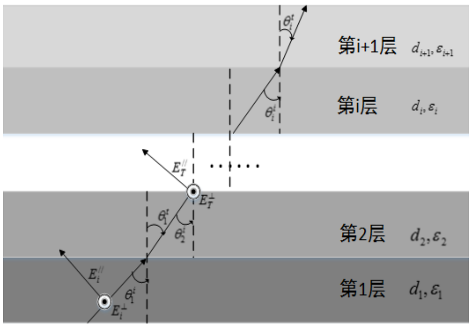

Fig.1. Plasma layered model.

When the incident angle is θ_i, the refraction angle θ_t can be obtained by the refraction theorem as:

$$\theta_t = arcsin(\frac{\sqrt{\mu_2 \varepsilon_2}}{\sqrt{\mu_1 \varepsilon_1}} sin\,\theta_i) \tag{4}$$

When electromagnetic waves pass through the interface of the layered media, transmission and reflection occur, and the electric field changes accordingly. Assuming that the incident wave is a plane wave, considering oblique incidence under normal circumstances, regardless of the polarization mode of the incident wave, it can be decomposed into two orthogonal linearly polarized waves: TE waves whose polarization direction is perpendicular to the plane of incidence, Polarization direction TM wave in the incident plane. It is assumed that the direction of polarization of the linearly polarized wave after passing through the interface does not change. The transmission coefficients of parallel polarized waves and vertically polarized waves can be obtained by using the boundary conditions [8]:

$$T_{\parallel} = \frac{2Z_2\cos\theta_i}{Z_1\cos\theta_i + Z_2\cos\theta_t} = \frac{2\frac{\varepsilon_2}{\varepsilon_1}\cos\theta_i}{\frac{\varepsilon_2}{\varepsilon_1}\cos\theta_i - \sqrt{\frac{\varepsilon_2}{\varepsilon_1} - \sin^2\theta_i}} \tag{5}$$

$$T_{\perp} = \frac{2Z_2\cos\theta_i}{Z_2\cos\theta_i + Z_1\cos\theta_t} = \frac{2\cos\theta_i}{\cos\theta_i + \sqrt{\frac{\varepsilon_2}{\varepsilon_1} - \sin^2\theta_i}} \tag{6}$$

Then calculate the transmission field in the next layer of media by projecting the electric field in the horizontal and vertical directions of the layer to multiply the transmission coefficient in the corresponding direction on the interface.

IV. Plasma Sheath Model and Split

Seven-component chemical reaction model simulated by the Zhejiang University Nie Liang et al[9] was used for calculating the flow field under different parameters of the hypersonic vehicle. Figure 3 shows the flow field with an altitude of 40 km, a speed of Mach 20 and an angle of attack of 0°.

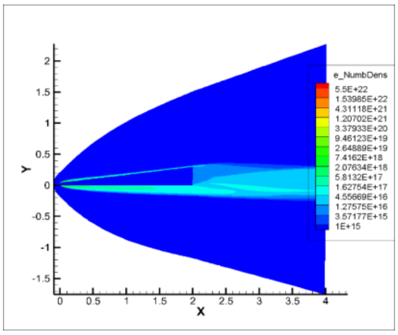

Fig.2. flow field model with a height of 40km, a speed of Mach 20 and an angle of attack of 0°.

Using a cuboid to wrap the entire flow field area and spliting a cuboid into many identical small cuboid units.The electron density of every cell is represented by the electron density of all discrete points that fall on it.

V. Results and Analysis

The grid meshes in the three directions of x, y, and z are 80, 80, and 80, respectively. The effects of different flying heights, different flight speeds, and different angles of attack on the antenna which is placed inside the aircraft and operating at 2.54 GHz are discussed.

A. Effect of aircraft flight height

The antenna was placed in a flow field with a Mach 20 speed and an attack angle of 0°, which were 30 km, 40 km, and 50 km. The radiation patterns of the two orthogonal planes were calculated as follows:

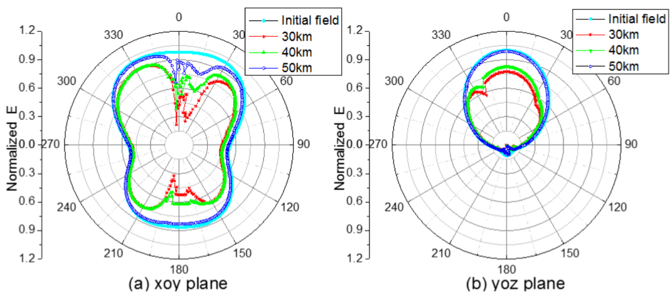

Fig.3. Antenna patterns with different aircraft height.

For figure 3(a), it can be clearly seen that the attenuation of the electric field on the xoy plane in the directions of 0 ° and 180 ° is relatively large, because it is directly opposite to the tip of the cone of the aircraft in the direction of 0 °. In this place the electron density is the largest in the entire sheath. At 180 ° is the "wake" of the sheath, electromagnetic waves need to propagates a very long distance in the plasma to get out. Compare to (a) and (b),it shows that the higher the height,the greater the attenuation of the electric field.

B. *Effect of aircraft speed*

When the antenna is placed in a flow field model with a height of 40 km, an angle of attack of 0 °, and speeds of Mach 15, Mach 20, and Mach 25, respectively. The radiation pattern of the three orthogonal planes was calculated as follows:

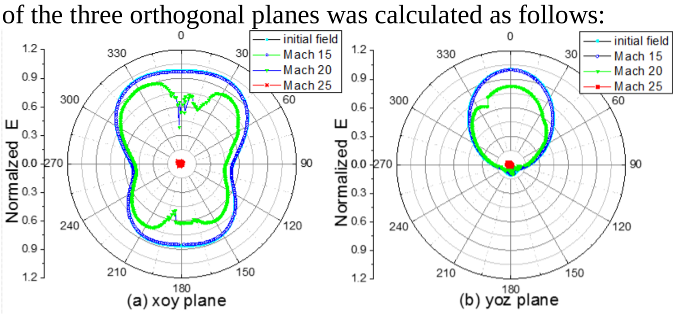

Fig.4. Antenna patterns with different aircraft speed.

The comparison is shown in figure 4. At a speed of Mach 15 the electric field will basically have no attenuation and the initial field will basically coincide. When the speed reach to Mach 25, the electric fields of the two planes are basically attenuated to 0, which is the so-called "Blackout".

C. *Effect of aircraft angle of attack*

When the aircraft is flying at a non-zero angle of attack, the pressure on both sides will not be symmetric about the central axis. This results in an asymmetric electron density distribution and will be greater at the windward side. We place antenna in a flow field model with a height of 30 km, a speed of Mach 20, and angles of attack of 0 °, 10 °, and 20 °, respectively. The radiation patterns of the three orthogonal planes were calculated as follows:

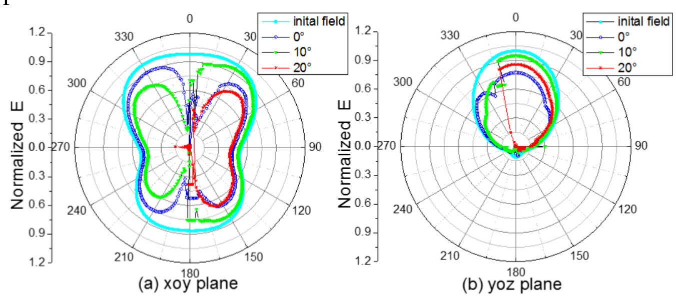

Fig.5. Antenna patterns under different aircraft height influences.

In the above figure 5, the increasing angle of attack increases the attenuation of the electric field in the left half plane of the yoz plane. When it reaches 20 °, the electric field in the left half plane decays to zero, because of the electrons in the sheath's tail. The denser flow field is basically deviated to one side of the sheath, and the attenuation of the electric field is minimal for the right half-plane with an angle of attack of 10 °.

VI. Conclusion

The ray tracing method was utilized to study the effect of the simulated plasma sheath on the radiation pattern of the antenna placed in it, and the attenuation of the electric field was calculated under different flight altitudes, speeds, and angles of attack. We got the following conclusions:

(1) In the case of the same speed and angle of attack, when the height of the aircraft is 30 km, the amplitude of the electric field radiated by the sheath to the antenna is the greatest, and the attenuation decreases as the altitude futher increases.

(2) the higher the speed is, the greater the overall electron density of the sheath flow field is, and the stronger the attenuation of the antenna.the communication will be interrupted when the speed reaches Mach 25, That is a "black-out" formed.

(3) the angle of attack has no obvious regularity in the attenuation of the electric field. When the angle of attack is 10 °, the attenuation is smaller than the other two angles. This feature can be helpful to appropriately adjust the angle of attack when the electric field is attenuated to sacrifice the electric field at certain angles to enhance the field at other angles to improve the communication quality.

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