Design Method of Wave Transmission Window of Satellite Fairing

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ABSTRACT

Satellite fairing with aluminium alloy honeycomb structure has shielding function to radio signal. To receive satellite signal to monitor the satellite status before discarding the fairing, it needs to open a wave transmission window in the fairing. According to the designated orbit of the launch vehicle and the position of station, the $\alpha$ and $\beta$ angles of measuring line of tracking launch vehicle or satellite are calculated at each time node, and the projective line of the measuring line on the shell is also calculated according to the relative location of the satellite antenna in the fairing. Then the minimum zone can be got which can receive the satellite signal. It realizes the monitoring of the satellite before discarding the satellite fairing, meanwhile, minimizes the infection to the structure strength of the fairing and ensures the safety of the fairing.

INTRODUCTION

As the protective cap of the satellite, the satellite fairing of launch vehicle prevents from the effect of dust, rain water, dampness, temperature, radiation when the satellite flies through the dense atmosphere. For it needs to endure the wind loads (atmospheric drag), vibration and the impact of rainwater during the flight, it needs enough strength and rigidity. Meanwhile, to improve the efficiency and carrying capacity, its mass need to be as light as possible[1]. So, most of satellite fairings are made of composite material and combined with alluminium alloy. The cylindrical section and inverse conical section of the fairing are usually made of alluminium honeycomb core material[2], which has high strucutral strength and low weight. To implement the wireless test of satellite and rocket on the launching tower, it needs to open the static wave transmission window in the fairing, and it brings more difficulty to the optimum design of the satellite firing[3].

In previous space missions, restricted by many factors such as the layout of satellite tracking telemetering and command network, the measurement and control requirement of payload, the requirement of strength of the fairing and so on, the ground measurement and control system provides support for tracking and control after the fairing is thrown away. That means a blind zone between the satellite launching and the fairing discarding. If there are exceptions of satellite occurred in this time, there will be no data for analysing and auditing. So, the satellite development department required to add a simple telemetry receiving equipment in the first zone recently, to make up the gap of telemetry in the fore section after satellite launching. In order to moniter the satellite status between the satellite launching and discarding the fairing, besides installing the telemetry equipment in the right place of the first zone (usually the top of a mountain to have a better perspective), it is need to set a wave transmission window
in the satellite firing. It is a subject worthy of study where and how to set the wave transmission window to meet the demand of receiving signals during the rocket flight and the requirement of the fairing’s strength.

CALCULATION OF THE ANGLE $\alpha, \beta$ OF THE TRACKING STATION TO THE SATELLITE

First, calculate the angle $\alpha, \beta$ of the tracking station to the satellite according to the theoretical trajectory of launch vehicle and the coordinates of observation station, to get a series of $\alpha_i, \beta_i, i=1,2,3 \ldots \ldots$ which correspond to the time bodes of theoretical trajectory of the launch vehicle.

The Coordinates of Launching Workplace, $\vec{r}_{fsd}$, in Earth-center Earth-fixed Coordinate System (ECEF) [5]

The coordinates of launching workplace in ECEF:

$$\vec{r}_{fsd} = \begin{bmatrix} X_{fsd} \\ Y_{fsd} \\ Z_{fsd} \end{bmatrix} = \begin{bmatrix} (N_{fsd} + H_{fsd}) \cos B_{fsd} \cos L_{fsd} \\ (N_{fsd} + H_{fsd}) \cos B_{fsd} \sin L_{fsd} \\ N_{fsd}(1-e^2_{fsd}) + H_{fsd} \sin B_{fsd} \end{bmatrix}$$

where, $L_{fsd}, B_{fsd}, H_{fsd}$ are geodetic longitude, latitude and height of launching workplace respectively, $e$ is the eccentricity of earth reference ellipsoid, $a$ is the radius of earth equator.

The Postion Vector $\vec{r}_{cz}$ of the Station in ECEF

According to the parameters of the station location, the position vector of the station in ECEF system is:

$$\vec{r}_{cz} = \begin{bmatrix} X_{cz} \\ Y_{cz} \\ Z_{cz} \end{bmatrix} = \begin{bmatrix} (N_{cz} + H_{cz}) \cos B_{cz} \cos L_{cz} \\ (N_{cz} + H_{cz}) \cos B_{cz} \sin L_{cz} \\ N_{cz}(1-e^2_{cz}) + H_{cz} \sin B_{cz} \end{bmatrix}$$

where, $L_{cz}, B_{cz}, H_{cz}$ are geodetic longitude, latitude and height of the station respective.

Position Vector of the Station, $\vec{r}_{cz-fsd}$, in Launching Coordinates

According to the position vector of the station and the launching workplace in ECEF system, the astronomical longitude, latitude of the launching workplace, and the launching azimuth, the position vector of the station in launching system [5] can be calculated as


\[ \vec{r}_{c-fd} = \begin{pmatrix} X_{c-fd} \\ Y_{c-fd} \\ Z_{c-fd} \end{pmatrix} = G^{-1}(\vec{r}_c - \vec{r}_{fd}) \]

where, \( G \) is the rotation matrix from launching coordinate system to ECEF system:

\[ G = R_x(90^\circ - \lambda_{fd})R_y(-\phi_{fd})R_z(90^\circ + A_{fd}) \]

where, \( R_x(\theta), R_y(\theta), R_z(\theta) \) are rotation matrices revolving around the axis \( x, y, z \) counter-clockwise angle \( \theta \), \( \lambda_{fd}, \phi_{fd} \) are astronomical longitude and latitude of launching point, \( A_{fd} \) is the launching azimuth.

**Calculation of the Position \( \vec{r}_{c-\mu} \) of Station in the Rocket Coordinate System**

The position vector of the station in rocket system can be calculated from the positions of the station and the rocket in the launching system and the attitude angles of rocket

\[ \vec{r}_{c-\mu} = \begin{pmatrix} X_{c-\mu} \\ Y_{c-\mu} \\ Z_{c-\mu} \end{pmatrix} = E(\vec{r}_c - \vec{r}_{\mu}) \]

where, \( \vec{r}_{\mu} \) is the position vector of rocket in the launching coordinate system, \( E \) is the rotation matrix from launching coordinate system to rocket coordinate system:

\[ E = R_x(\Psi)R_y(\Phi)R_z(\Gamma) \]

where, \( \Phi, \Psi, \Gamma \) are the pitch, yaw and roll angles of the rocket in launching coordinate system respectively.

**Calculation of the Angle \( \alpha, \beta \) of the Measurement and Control Line in the Rocket Coordinate System**

From the position vector of station in rocket coordinate system, angle \( \alpha, \beta \) of the measurement and control line—the connecting line between the station and the rocket can be calculated as

\[ \alpha = \begin{cases} \arctg \left( \frac{Z_{c-\mu}}{Y_{c-\mu}} \right) & Y_{c-\mu} > 0, \ Z_{c-\mu} > 0 \\ \pi + \arctg \left( \frac{Z_{c-\mu}}{Y_{c-\mu}} \right) & Y_{c-\mu} < 0 \\ 2\pi + \arctg \left( \frac{Z_{c-\mu}}{Y_{c-\mu}} \right) & Y_{c-\mu} > 0, \ Z_{c-\mu} < 0 \end{cases} \]

\[ \beta = \arccos \left( \frac{X_{c-\mu}}{\sqrt{X_{c-\mu}^2 + Y_{c-\mu}^2 + Z_{c-\mu}^2}} \right) \]

where, \( \alpha \) is the angle between the projection of the measurement and control line in the rocket coordinate system \( OYZ \) plane and \( Y \) axis, \( \alpha \in [0^\circ, 360^\circ] \); angle \( \beta \) is the angle between the measurement and control line and \( \chi \) axis of the rocket coordinate system, \( \beta \in [0^\circ, 180^\circ] \).

For the difference between the barycenter of carrier rocket, \( \rho \) and the position of spaceborne antenna can be neglected in the case of the large scale, the angle \( \alpha, \beta \) in the rocket coordinate system calculated above can be regarded as the angle in the
quasi-body coordinate system, \( O_{j}'x'j'y'j'z'j' \), whose origin has been moved from the barycenter, \( O_{j} \), of the rocket to the position of antenna, \( O_{j}' \). Figure 1 is the diagram of angle \( \alpha \), \( \beta \) of measurement and control line in the quasi-body coordinate system, \( O_{j}'x'j'y'j'z'j' \), whose origin is the position of the satellite antenna.

![Diagram of \( \alpha \), \( \beta \) of measurement and control line.](image)

According to the theoretical trajectory of the corrier rocket and computing method of angle \( \alpha \) forementioned, a series of angles \( \alpha_{i} \), \( i=1,2,3, \ldots \) can be got which are corresponding to the theoretical trajectory at each time node; likewise a series of angle \( \beta_{i} \), \( i=1,2,3, \ldots \) can be got.

**CALCULATION OF THE TRACK OF THE MEASUREMENT AND CONTROL LINE ON THE COVERING OF THE SATELLITE FAIRING**

**The Length of the Track Arc of the Measurement and Control Line in the Cross Section Relative to the \( Y_{j} \) Axis**\(^{[6]}\)

From the angles \( \alpha \), \( \beta \) of the measurement and control line in the rocket coordinate system, the design data of the satellite fairing and the position of the antenna in the rocket coordinate system, the track of the measurement and control line one the covering of the satellite fairing can be calculated as:

\[
\angle O'_{j}O'D = \angle O'_{j}O'_{E} = \arctg \left( \frac{\overline{O'D}}{\overline{O'E}} \right) = \arctg \left( \frac{a}{b} \right)
\]

where, \( O'_{j} \) is the position of the antenna in the cross section of the rocket, \( O'_{j} \) is the intersection of the cross section and the rocket vertical axis. Translate the origin of body coordinate system to \( O'_{j} \) to get the quasi-body coordinate system, \( O'_{j}x'j'y'j'z'j' \), then \( \overline{O'D} = \overline{EO'} = a \) is the distance between the satellite antenna and axis \( O'_{j}y'j' \), \( \overline{EO'} = \overline{O'D} = b \) is the distance between the satellite antenna and axis \( O'_{j}z'j' \) (See Figure 2 and Figure 4).
Figure 2. Diagram a of angle $\alpha$ of the measurement and control line.

Figure 3. Diagram b of angle $\alpha$ of the measurement and control line.

$$\angle AO'\Omega' = 2\pi - \angle O'\Omega'\xi - \angle E\Omega'\Omega$$

$$= 2\pi - \arctg \left( \frac{a}{b} \right) - \alpha$$

In $\triangle O'\Omega'\Omega$, based on sine theorem

$$\frac{\sin \angle O'\Omega'\Omega'}{O'\Omega'} = \frac{\sin \angle O\Omega'\Omega'}{O\Omega}$$

there is

$$\angle O'\Omega'\Omega' = \arcsin \left( \frac{O\Omega'}{O'\Omega'} \sin \angle O\Omega'\Omega' \right)$$

$$= \arcsin \left( \frac{\sqrt{a^2 + b^2}}{d} \sin \angle O\Omega'\Omega' \right)$$

where, $d$ is the diameter of the satellite fairing.

As shown in Figure 2, when

$$\alpha \geq \left( \pi - \arctg \left( \frac{a}{b} \right) \right), \quad \alpha^* = \alpha - \angle O'\Omega'\Omega';$$

As shown in Figure 3, when
\[ \alpha < \left( \pi - \arctg \left( \frac{a}{b} \right) \right), \quad \alpha^* = \alpha + \angle O'_{\alpha}AO'. \]

As shown in Figure 2 and 3, the length of the arc in the cross section between \( A \) (the intersection of the track of measurement and control line and the fairing covering) and the start point \( C \) (intersection of \( y_j \) axis of rocket coordinate system and the fairing covering), \( CBA \), can be calculated as:

\[ CBA = d \cdot \alpha^* \]

where, the unit of \( \alpha^* \) is radian.

### The Length of the Track Arc of the Measurement and Control Line in the Lengthwise Section Relative to the Satellite Antenna \([6]\)

From Figure 2 and 3, it’s easy to get the distance \( OA' \) between points \( O \) and \( A \). In \( \Delta AO'O' \), based on cosine theorem, there is

\[
\overline{OA'}^2 = \overline{O'A'}^2 + \overline{O'O'}^2 - 2 \cdot \overline{O'A'} \cdot \overline{O'O'} \cdot \cos \angle AO'O'
\]

\[
= d^2 + (a^2 + b^2) - 2d\sqrt{a^2 + b^2} \cos \angle AO'O'
\]

\[
= d^2 + (a^2 + b^2) - 2d\sqrt{a^2 + b^2} \cos (\pi - \angle AO'O' - \angle O'A'AO')
\]

From Figure 4, the trace of measurement and control line in the lengthwise section relative to the satellite antenna can be calculated as:

\[
\overline{AT} = \frac{\overline{OA}}{\sqrt{\beta}}
\]

![Diagram of angle \( \beta \) of the measurement and control line.](image)

**Figure 4. Diagram of angle \( \beta \) of the measurement and control line.**

### Design Method of Wave Transmission Window of Satellite Fairing

Cut the covering of fairing column section along the third quadrant line \([5]\), and expand to a rectangle, set up a coordinate system of column section of the fairing covering (See Figure 5): the original point \( o_z \) is the intersection point of the bottom circumference of the column section (coincide with the satellite mounting surface) and the 3rd quadrant line; \( x_z \) axis coincides with the developed bottom circumference of the column section, and points to the direction of the 4th quadrant line; \( y_z \) axis coincides with the 3rd quadrant line, and points to rocket head (in accordance with the \( x_j \) axis of rocket coordinate system).
The coordinates of the trace of the measurement and control line in the plane coordinate system of covering of the column section of the fairing, \((x_c, y_c)\) can be got as
\[
x_c = CBA = d \cdot \alpha^*
\]
\[
y_c = \begin{cases} 
AT + c & \text{when } \beta \leq 90^\circ \\
-AT + c & \text{when } \beta > 90^\circ 
\end{cases}
\]

Where, \(c\) is the distance between the satellite antenna and the underside of satellite fairing column section (satellite installation surface).

From the consecutive measurement and control line \(\alpha_i\) and \(\beta_i\), \(i=1,2,3,\ldots\) in the tracking arc, a series of coordinates \((x_{zi}, y_{zi})\) of the trace of the measurement and control line can be got in the covering of the column section of the fairing, as the dark slimline shown in Figure 5.

Finally, according to size of the antenna, the beam width to pass through the fairing covering can be determined, then the open area of the wave transmission window of the fairing can be got as shown in Figure 5, the light-colored area out of the track of the measurement and control line. For example: If the maximum size of the antenna is 10cm, the beam width to pass through the fairing covering is amplified to 12cm, then the open area of the wave transmission window is an area of a circle with a radius of 6cm whose center moves along the trace of the measurement and control line.

**CONCLUSIONS**

The design method of the wave transmission window of the fairing presented in this paper makes full use of the position relations among the launching workplace, station and the rocket, and the attitude of the rocket, the position of the antenna on the rocket. It realizes the exact design of the position and size of the wave transmission window, meet the demands of telemetry of specific station in the launch section, meanwhile it minimized the size of the wave transmission window to prevent from excessive reduction of the structure strength of the fairing which affect its security.
REFERENCES