Rocket Rolling Attitude Determining Method Based on Optical Tracking Measurement

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Abstract. The rocket attitude is used to describe the attitude and state of the carrier rocket moving around its mass center and is also an important parameter used to evaluate the stability of the rocket movement. Aimed at the problem that it is difficult to determine the optical tracking measurement-based rocket rolling attitude, special positions in the rocket video image are selected skillfully to perform the measurement interpretation, establish corresponding rolling attitude calculation model, model and analyze the carrier rolling attitude changes caused by the measurement interpretation error. This method not only expands the data processing method used to select the rolling attitude measurement for interpretation, but also provides effective judging basis for analyzing, evaluating and improving the rocket performance.

1. Introduction
It is an important task to measure and calculate the carrier rolling attitude in the spaceflight test range. It is an important parameter to evaluate the movement posture, state and stability. In addition, it is also an important evaluation basis of judging whether the attitude angle deviation of attitude control system and control accuracy of center-of-mass coordinate deviating from the given value meet the design requirements[1-2].

In the measurement of rocket rolling attitude, high-speed TV measurement system laid in the range is used to track and measure some special marks on the rocket in general, namely the red mark blocks painted on the rocket for the rolling attitude measurement. Then the rocket attitude is obtained after image data interpretation and calculation so as to describe the dynamic process of rocket attitude accurately. Therefore, it provides effective basis for the model research development on analyzing the stability, safety and flight performance of the vertical take-off section. However, impacted by atmospheric disturbance, instrument pointing, smaller angle with the sun and reduction of contrast ratio between target and background, the image of a series of red mark blocks used to measure the rocket rolling attitude is blurred. The blurred image has a serious influence on the interpretation and extraction of the measurement data obtained from the red mark blocks. And it is impossible to calculate and determine the rocket rolling attitude, resulting in an obstacle for evaluating the flight performance of the rocket. Therefore, it is necessary to find out other method.

This paper provides a calculation method for rocket rolling attitude based on other imaging marks on the rocket. The special marks used for imaging measurement of carrier rocket are fully used in this method. Even though in case of not obtaining the measurement data of red mark blocks, this method also can be used to measure and calculate the rocket rolling attitude. Tested in the actual tasks, this method not only determines the rolling attitude of the rocket accurately, but also provides important support for the model department on improving the rocket structure, perfecting the test and launch system performance and enhancing the launch safety.
2. Selection of measurement interpretation position

The method of marking spiral line on the rocket to measure and calculate the rocket rolling attitude is introduced in literature [3-5]. In literature [6], the red mark blocks used for measuring the rolling attitude are fully used in the interpretation position selection, data collection and establishing of rolling attitude calculation model. Moreover, the influences of different pixel interpolations on the rolling attitude are analyzed in literature [6]. Fig.1 is the outline drawing of XX-XX model rocket. As shown in the Figure, there are red blocks used for the rocket rolling attitude on the rocket booster and the upper end of the second level. However, in actual test tasks, when it is impossible to extract the red blocks, it is necessary to find out other solution to measure and calculate the rocket rolling attitude. Based on actual imaging situation of the rocket, special imaging marks are used to measure, interpret and calculate the rocket rolling attitude in this paper.

![Fig.1 Outline drawing of XX-XX model rocket](image1)

With the observation on the distribution of tracking devices and analysis on imaging of marks on the rocket, the obvious imaging marks (national flag) on the rocket can be fully used to measure and calculate the rocket rolling attitude. As seen from the fairing in Figure 1, the Five-Starred Red Flag is prominently positioned and is easy to be interpreted and measured in the video image. Fig.2 is the rocket local magnification drawing observed by two observing stations, where the imaging situation of the Five-Starred Red Flag mark forms the measurement data selection positions: the feature positions of the side of rocket imaging and the side of national flag.

![Fig.2 Rocket local magnification drawing](image2)

(a) National flag imaging diagram obtained in measuring station 1
3. Imaging position interpretation and correction

Fig. 3 is the measurement diagram of rolling angle, where $s$ is the projection center of high-speed cinematography instrument tracking device; $m$ (measurement data selection position 1) is the imaging position point of the national flag (upper edge or lower edge) on the edge of the rocket; $s m'$ is the direction of the projection center to the rocket edge; $n$ (measurement data selection position 2) is the other edge point (The selection of upper edge or lower edge is the same with the selection of m.) of the national flag; $s n'$ is the interpretation point direction of the target; $r$ is the radius of the rocket; $R$ is the distance between the measuring station and launch origin. Since the measuring station is far away from the launch center, it is considered that $s$, $o$, $m$ and $n$ are in the same plane.

![Fig.3 Rolling angle measurement diagram](image)

The following formula can be drawn from Fig. 3.

$$\angle \text{mse} = \arcsin(r/R) \tag{1}$$

According to the imaging principle and interpretation system, measuring angle measured data of $m$ and $n$ relative to the principal optical axis can be obtained, namely[7]

$$\begin{align*}
A_j' &= \arctg\left(\frac{x_j}{f \cos E_j - y_j \sin E_j}\right) + A_j \\
E_j' &= \arcsin\left(\frac{f \sin E_j + y_j \cos E_j}{\sqrt{f^2 + x_j^2 + y_j^2}}\right) \\
&= \begin{cases} 
A_j' + \Delta A_0 + tg(E_j' + \Delta E_0)[b + I \sin(A_{ii} - A_j' - \Delta A_0)] + c \sec(E_j' + \Delta E_0) & j = m, n
\end{cases} \tag{2}
\end{align*}$$

Where $A_j$ and $E_j$ are the target measuring angle data obtained during interpreting $m$ and $n$ respectively. $f$ is the photographic focal length; $x_j$ and $y_j$ are the tracking error of $m$ and $n$ in the photo coordinate system respectively.

Systematic error correction is carried out to formula (2). The azimuth data of $m$ and $n$ are obtained, namely

$$A_j'' = A_j' + \Delta A_0 + \frac{tg(E_j' + \Delta E_0)[b + I \sin(A_{ii} - A_j' - \Delta A_0)] + c \sec(E_j' + \Delta E_0)}{j = m, n} \tag{3}$$

Where $\Delta A_0$ and $\Delta E_0$ are system zero error; $b$ is the error of horizontal axis; $i$ is the error of vertical axis; $A_{ii}$ is the azimuth of vertical axis in the inclined direction; $c$ is the sighting error.
4. Calculation method

4.1. Modelling of rolling attitude

Based on the azimuth obtained from formula (3), the following formula can be obtained:

\[ \angle m'sn' = A'_m - A'_n \]  \hspace{1cm} (4)

Then

\[ \Delta A = \arcsin(r/R) - \angle m'sn' \]  \hspace{1cm} (5)

Combined with Figure 3, given \( g_0=a, g_n=b, s_n=c, \angle gon=\gamma, \) then

\[ r^2 = c^2 + R^2 - 2R \cdot c \cdot \cos \Delta A \]

The following values can be solved:

\[ c = R \cos \Delta A \pm \sqrt{r^2 - R^2 \sin^2 \Delta A} \]  \hspace{1cm} (6)

\[ \gamma = \sin^{-1} \frac{b}{r} = \sin^{-1} \frac{\sin \Delta A \cdot c}{r} = \sin^{-1} \frac{\sin \Delta A (R \cos \Delta A - \sqrt{r^2 - R^2 \sin^2 \Delta A})}{r} \]  \hspace{1cm} (7)

In formula (6), the symbol ± in front of the second term is only regarded as “+”. If the symbol is regarded as “−”, when the measuring point \( n \) approaches to the measuring point \( e \), \( c > R \) will occur, however, it is contradictory.

So the rolling angle is determined

\[ \alpha_i = \gamma_i - \gamma_0 \]  \hspace{1cm} (8)

Where, \( \alpha_i \) is the rolling angle at moment \( i \); \( \gamma_i \) is the rolling angle at moment \( i \); \( \gamma_0 \) is the rolling angle at moment \( t_0 \).

4.2. Error analysis

It can be seen from formula (7) that the main factors influencing the calculation accuracy of rocket rolling attitude include \( R \) and \( \Delta A \). \( R \) is the distance between measuring station to launch origin, and its accuracy is determined by the geodetic survey result; The accuracy of \( \Delta A \) relates to the interpretation result of feature point position. The variation relation of each error term is obtained with the error variation technique:

\[ \delta \gamma = \frac{B^{-1/2} R \sin^3 \Delta A}{[r^2 \cos^2 \Delta A + R \sin^2 \Delta A (2B^{1/2} \cos \Delta A + R - 2R \cos^2 \Delta A)]^{1/2}} \delta R \]

\[ - \frac{B^{1/2} \cos \Delta A (1 + R^2 \sin^2 \Delta A)}{[r^2 \cos^2 \Delta A + R \sin^2 \Delta A (2B^{1/2} \cos \Delta A + R - 2R \cos^2 \Delta A)]^{1/2}} \delta \Delta A \]

(9)

Where \( B = (r^2 - R^2 \sin \Delta A) \).

Taking the rocket of a certain model, launch direction and corresponding station distribution as an example, the above method is used to carry out the data simulation analysis. The influence of interpretation error on the rocket rolling attitude at the azimuth and pitch directions is analyzed respectively.

Fig.4 and Fig.5 are the influence data graphs of interpretation error of azimuth and pitch on the rocket rolling attitude respectively.
As shown in Fig. 4, disturbing quantities of 250 arc-second, 500 arc-second and 750 arc-second are given on the azimuth error to analyze its influence on the rocket rolling attitude. As shown in Fig. 5, disturbing quantities of 250 arc-second, 500 arc-second and 750 arc-second are given on the pitch error to analyze its influence on the rocket rolling attitude. It can be seen from the two figures that the azimuth error has much greater influence on the rocket rolling attitude than the pitch error. And with the time goes on, the error influence shows a monotonic upward trend. Therefore, it is necessary to aim at the measuring point during interpreting the measuring points m and n so as to obtain accurate interpretation, reduce the tracking error in direction xj as much as possible and improve the determination accuracy of rocket rolling attitude.

5. Conclusion
This paper fully applies special imaging marks on the rocket, puts forward data collection interpretation method of effective feature points, establishes reliable and practical mathematical model and algorithm for the rocket rolling attitude. In addition, the disturbance of rocket rolling caused by the interpretation error is also modeled in this paper. Even though when it is impossible to extract the given rolling measurement marks, it is also able to measure and calculate the rocket rolling attitude in the vertical take-off section, providing a new way for data processing.

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