Thrust line measurement of multi-nozzle solid rocket engine

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Abstract

Static thrust line is an important measuring parameter of solid rocket engine. Factors that affect the misalignment and deflection of thrust line of multi-nozzle solid rocket engine were analysed in static condition, and a measuring method by Laser Tracker for thrust line was researched. A calculation model of the thrust line was established based on simplified force spiral rule, which synthesizes the space force systems. The simulation results of misalignment and deflection indicate that the method has high measurement accuracy.

Keywords: solid rocket motor, static thrust line, multi-nozzle, laser tracker

1 Introduction

Before shipment, various geometric parameters of solid rocket motor need to be measured accurately under static conditions. Misalignment and deflection of the engine's thrust line are very critical parameters. The misalignment indicates the vertical distance between the thrust line and the engine axis in space. The deflection refers to the angle of the vector with the engine axis of the thrust line in space, the two parameters directly affect the pitch and yaw of the rocket during the flight to control the attitude [1].

Thrust of rocket engine is generated like this, jet flow from burning huge quantities of fuel acts upon internal curved surface of the nozzle, therefore static thrust line can be substituted by the geometry centreline of the surface. The thrust line of multi-nozzle solid rocket engine can be obtained by synthesizing the thrust produced by each nozzle, while the factors affect the thrust line are due to the deviation relative to the theoretical position of nozzles in the engine. During the machining and assembling process, the deviations of engine nozzle parts exists inevitably, and owning to the accumulation and amplification, will affect the action points and direction of each thrust line. Thus, the misalignment and deflection will be brought in the synthesis of thrust line eventually [3, 4].

In the past for a long time, under static conditions, the thrust line of a single nozzle is substituted by the connection from the centre of the throat neck and the centre of the nozzle outlet end face. Meanwhile, in multi-nozzle engine, the synthesis of the thrust line is calculated based on the arithmetic average of each centre of the throat neck and the nozzle's outlet end face indirectly, apparently there will be deviation in principle. In [5], we have already researched the measuring technology of a solid rocket engine with single nozzle's structure. In this letter, a four-nozzle solid rocket motor is taken as a measuring object, the thrust line measurement on multi-nozzle engine and data processing methods are studied further to achieve efficient and accurate results.

2 Static thrust line measurement of single nozzle rocket engine

The measurement of a single nozzle's thrust line can be realized by surveying the geometric centreline of the internal surface, which is determined by the centres of the nozzle throat neck and outlet. In the geometric measuring point of view, typically, between the nozzle throat neck and outlet end face, a number of cross-sections of the nozzle parallel to the outlet plane are needed to be measured in order to improve accuracy, and then the geometry centreline is fitted from these sections' centres by least square method. The measurement diagram is shown in Figure 1.

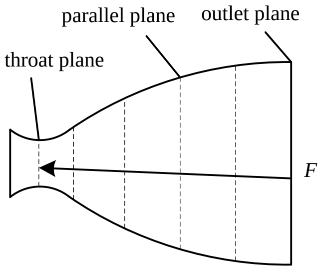

FIGURE 1 Diagram of thrust line measurement

After fitting, the space equation of the thrust line F can be expressed as Equation (1) shows.

$$\frac{x-x_1}{l_1}=\frac{y-y_1}{m_1}=\frac{z-z_1}{n_1}\,. \tag{1}$$

For multi-nozzle solid rocket motor, the same method can be applied to get the other nozzles' thrust line equations.

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3 Static thrust line analysis of multi-nozzle rocket engine

According to the force translational theorem of rigid body in theoretical mechanics, any force system acting on the same rigid body can be simplified to any point and synthesized into a resultant force and an additional spatial force couple. In multi-nozzle engine, the action points and direction of each sub-thrust are different; in order to calculate the misalignment and deflection of the synthesis engine thrust line, each nozzle's thrust vector needs to be simplified and synthesized of the space force.

Assume that the direction number of the thrust line F_1 is (l_1, m_1, n_1), the action point's coordinate is (x_1, y_1, z_1); the direction number of the thrust line F_2 is (l_2, m_2, n_2), the action point's coordinate is (x_2, y_2, z_2); the direction number of the thrust line F_3 is (l_3, m_3, n_3), the action point's coordinate is (x_3, y_3, z_3); the direction number of the thrust line F_4 is (l_4, m_4, n_4), and the action point's coordinate is (x_4, y_4, z_4), the distribution of each thrust's vector is shown in Figure 2, the illustrated coordinate system is the product coordinate system of the engine.

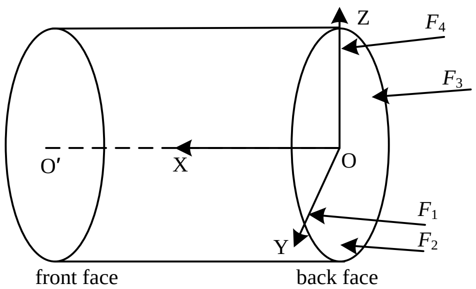

FIGURE 2 Diagram of thrust forces distribution of multi-nozzle

Decompose the thrust component along each coordinate axis of the product coordinate system and then synthesize them in each axis direction separately, the component of the resultant force can be obtained as shown in Equation (2).

According to the calculation by Equation (2), all the force components along the coordinate axis direction can synthesize the magnitude and direction of the resultant thrust line Fc based on projection and analysis.

$$\begin{cases} F_x = \sum_{i=1}^{4} F_i l_i \\ F_y = \sum_{i=1}^{4} F_i m_i \\ F_z = \sum_{i=1}^{4} F_i n_i \end{cases} . \quad (2)$$

The magnitude and direction of Fc is shown as below in Equation (3).

$$\begin{cases} F_c = \sqrt{F_x^2 + F_y^2 + F_z^2} \\ l_{F_c} = \dfrac{F_x}{F_c} \\ m_{F_c} = \dfrac{F_y}{F_c} \\ n_{F_c} = \dfrac{F_z}{F_c} \end{cases} . \quad (3)$$

When each component of thrust is simplified to the origin of coordinate system, the additional space moment of couple is shown as below in Equation (4).

$$\begin{aligned} M_x &= \sum_{i=1}^{4} F_i \left(n_i y_i - m_i z_i \right) \\ M_y &= \sum_{i=1}^{4} F_i \left(l_i z_i - n_i x_i \right) \\ M_z &= \sum_{i=1}^{4} F_i \left(m_i x_i - l_i y_i \right) \end{aligned} . \quad (4)$$

According to the calculation by Equation (4), the synthesis results and direction of the resultant additional couple moment Mc also can be calculated based on projection and analysis as Equation (5) shows.

$$\begin{cases} M_c = \sqrt{M_x^2 + M_y^2 + M_z^2} \\ l_{M_c} = \dfrac{M_x}{M_c} \\ m_{M_c} = \dfrac{M_y}{M_c} \\ n_{M_c} = \dfrac{M_z}{M_c} \end{cases} . \quad (5)$$

Due to the influence of the deviation in machining and assembling process, each nozzle thrust of multi-nozzle solid rocket motor in space inevitably acts as non-converging system of forces, and cannot be a parallel forces system. Thus, the results of the thrust component simplified to the origin of product coordinate system need to be further simplified to synthetic force screw, as shown in Figure 3, then the principal vector Fc is the physically meaningful synthetic thrust line.

The synthesis process of force screw is as follows: first build the auxiliary space coordinate system parallel to Fc according to Equation (3), project and decompose the additional moment of couple under the coordinate system built above on the basis of Equation (5), the relative coordinates of the main vector which need to be translated can be obtained in the force spiral synthesis process. Then in accordance with the spatial relationships between the products and auxiliary coordinate systems, convert translational coordinates of the principal vector into the product coordinate system, the coordinates of the feature points of the principal vector equation can be acquired, and finally the equation of synthesis thrust line is achieved.

The process is realized in specific data-processing software based on Visual Basic language.

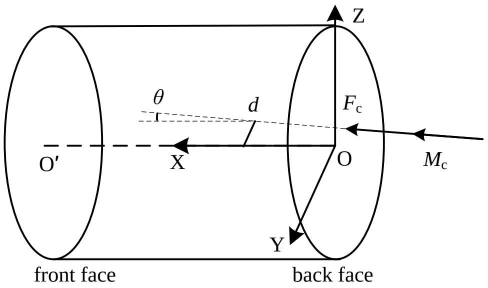

FIGURE 3 Diagram of simplified force screw

Based on the theory above, the line distance equation and angle equation in space, the misalignment *d* and the deflection *θ* of the synthetic thrust line can be calculated in Equations (6) and (7).

$$d = \frac{\begin{vmatrix} x_1 - x_2 & y_1 - y_2 & z_1 - z_2 \\ l_1 & m_1 & n_1 \\ l_2 & m_2 & n_2 \end{vmatrix}}{\sqrt{\begin{vmatrix} m_1 & n_1 \\ m_2 & n_2 \end{vmatrix}^2 + \begin{vmatrix} n_1 & l_1 \\ n_2 & l_2 \end{vmatrix}^2 + \begin{vmatrix} l_1 & m_1 \\ l_2 & m_2 \end{vmatrix}^2}}, \tag{6}$$

$$\theta = \arccos\left(\frac{l_1 \cdot l_2 + m_1 \cdot m_2 + n_1 \cdot n_2}{\sqrt{l_1^2 + m_1^2 + n_1^2} \cdot \sqrt{l_2^2 + m_2^2 + n_2^2}} \right). \tag{7}$$

4 Simulation

Firstly, the engine product coordinate system is defined, the X-axis is the centreline from the engine front and rear skirts of the end face, i.e. the engine reference axis, the Y-axis is determined by the first quadrant of engraved line of the rear skirt, and the Z-axis is determined by the right-hand rule.

Secondly, according to the definition of the thrust line, use the internal grate of the nozzle as the reference plane, measure 8 uniform sampling points which are set on a circle of the internal throttle of the nozzle in the engine product coordinate system.

Thirdly，according to the definition of the thrust line, use the internal end face of the nozzle outlet as the reference plane, measure 8 uniformly distributed sampling points, which are set on a circle of the outlet end face of the nozzle in the engine product coordinate system [6].

Finally, fit the simulation coordinates obtained above separately, which are on the laryngeal neck and the nozzle outlet end, the fitted centre coordinates is as shown in Table 1.

TABLE 1 Fitting results of nozzle throat and outlet

No.	x (mm)	y (mm)	z (mm)
1	0.12	-365.16	0.21
2	0.04	364.95	0.13
3	-0.09	-0.17	365.16
4	-0.41	0.02	-365.01
5	-400.03	-365.04	-0.13
6	-400.01	365.14	-0.07
7	-399.94	0.11	364.88
8	-399.91	0.05	-365.09

By fitting the results in Table 1 respectively, each space expression of the thrust component can be obtained.

In accordance with the force screw synthetic rule, the space equation of the synthetic thrust line (to ensure the accuracy of calculation, the coordinates of the feature points are retained to six decimal) is as shown in Equation (8).

$$\frac{x}{1} = \frac{y + 0.112834}{-0.000388} = \frac{z - 0.000114}{0.000563}. \tag{8}$$

Based on Equations (6) and (7), the misalignment and deflection of the thrust line are separately calculated, the results is illustrated in Table 2. Other processing results are listed in the table simultaneously, which use geometric mean method based on centre points of the end face of the throttle and nozzle outlet.

TABLE 2 Results of thrust line measurement

Method	misalignment (mm)	deflection (′)
force screw	0.093	2.349
geometric mean	0.005	2.349

From Table 2, we can see that the two methods have a large deviation between the misalignments, while no deviation between the deflections of the thrust line. This is because the decomposition and synthesis operation to the space force system axis has a linear relationship with the geometric mean arithmetic, and has the same effect in space; while in the geometric mean method, the role of space additional couple is not considered, thus a larger schematic deviation exists.

5 Conclusions

On the basis of the measurement technology of a single nozzle solid rocket motor’s thrust line, multi-nozzle static thrust line measurement techniques were researched using laser tracker, a space geometry model of synthetic static thrust line was established according to the synthetic force screw rule, and the equation was given. The simulation showed that the measuring techniques we introduced could overcome the principle error of the geometric mean method, and had higher accuracy.

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