Numerical research on jet tab thrust vector nozzle aerodynamic characteristics

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Abstract. Jet tab thrust vector nozzle is a unique kind of thrust vector device which generates control force by inserting tab into the nozzle exhaust. The influence of tab geometric parameters on the nozzle aerodynamic characteristics is not clear. In order to meet the requirements of control rate modeling and optimization of jet tab thrust vector control system, a computational study was conducted to investigate the effects of tab geometric parameters which include insertion height, width, axial distance, incline angle on nozzle aerodynamic characteristics. The flow structure of nozzle with different tabs are demonstrated, and thrust vector performance is evaluated. Results indicate that the lateral force coefficient and the thrust loss coefficient increased with the increase of the tab insertion height, the thrust vector efficiency decreased as the insertion height increased; increasing tab width increased the thrust vector efficiency, the thrust vector efficiency increased by 24.8% when the tab width increased form 10mm to 18mm; both increasing axial distance and increasing tilt angle decreased the lateral force and efficiency, in practical application, the axial position and incline angle should be minimized.

1. Introduction

The jet tab thrust vector control technology deflects the jet from the nozzle axis by inserting tab into the nozzle exhaust, utilizing the complex flow phenomena such as boundary layer separation upstream of the tab to achieve thrust vector control. The jet tab thrust vector control technology is unique. At present, this control technology is only applied to the Russian R-73 missile and its derivative models. Compared with the gas rudder commonly used in advanced air-to-air missiles, jet tab has outstanding advantages of no additional thrust loss, fast response and large control force [1]. And it has broad application potential in the field of vertical launching missiles and ejection seats [2-4].

Since the 1960s, Hollstein HJ and Eatough RG have conducted a series of cold- and hot-flow tests on jet tab thrust vector control technology, they developed performance prediction methods based on theoretical analysis and experimental data and evaluated the engineering application value of the technology [5-8]. In recent years, some researchers have studied this technology through numerical simulation and experimental methods. Yang Xiaoguang [9] analyzed the mechanical structure of the jet tab thrust vector control system applied to the Russian R-73 missile. Zhong Hua [4] carried out a
theoretical analysis on the working principle of the jet tab thrust vector nozzle, and carried out a series of static and dynamic tests to verify the use of the jet tab thrust vector nozzle to control the rocket thrust direction of the ejection seat. Han Wenchao [10], Cui Yebing [11], Li Guozhan [12] and others studied the flow characteristics and performance of jet tab thrust vector nozzles by numerical simulation.

In order to meet the requirements of control rate modeling and optimization of jet tab thrust vector control system, it is necessary to study the influence of jet tab geometry parameters on nozzle thrust vector characteristics. However, due to the complex flow phenomena such as boundary layer separation and shock boundary layer interference in the flow field of the jet tab thrust vector nozzle, the influence of the geometric parameters of the jet tab on the nozzle aerodynamic characteristics is not clear. In this paper, a computational study was conducted to investigate the effects of tab geometric parameters which include insertion height, width, axial distance, incline angle on nozzle aerodynamic characteristics.

2. Principle of jet tab thrust vector control technology

The flow field structure of the jet tab thrust vector nozzle is shown in Figure 1. When the jet tab is inserted into the nozzle exhaust, it will block part of the exit area, which directly causes oblique shock waves in the expansion section of the nozzle, accompanied by boundary layer separation, and the pressure in the separation area after the shock is far greater than the pressure before the separation point, an asymmetric pressure distribution will occur on the inner wall of the nozzle, resulting in lateral control forces. The oblique shock wave and the bow shock wave form a high pressure region on the windward side of the jet tab, so that the jet tab is subjected to a force opposite to the thrust direction of the nozzle, thereby causing the thrust loss of the nozzle. The thrust vector analysis is shown in Figure 2. $F_{AO}$ is the initial axial thrust when the jet tab is not inserted. $F_{R}$ is the total thrust after the jet tab is inserted, $F_{A}$ is the axial thrust, and $F_{S}$ is the lateral force.

The axial thrust loss could be defined as: $\Delta F_{A} = F_{AO} - F_{A}$

The lateral force coefficient could be defined as: $C_{S} = (F_{S} / F_{AO}) \times 100\%$

The axial thrust loss coefficient could be defined as: $C_{A} = (\Delta F_{A} / F_{AO}) \times 100\%$

Thrust vector efficiency could be defined as: $\eta = F_{S} / \Delta F_{A}$

3. Numerical simulation method

The solver for solving the Reynolds average Navier-Stockes equation is selected; the spatial discrete method is the finite volume method, the non-viscous flux is discretized by the Roe format, and the viscous flux is discretized by the central difference format. The time advancement method adopts the LU-SGS (Low Upper Symmetric Gauss Seidel) implicit method. The turbulence model uses the Realizable $k-\varepsilon$ model of the two equations, and the enhanced wall treatment is used near the wall.

4. Calculation model and boundary conditions

The shape of axisymmetric nozzle used in the numerical simulation is shown in Figure 3. The nozzle expansion area ratio was 6.25, and the design pressure ratio $NPR = 67.2$. The total pressure at the inlet of nozzle $p_{0}=7.2$MPa, the total temperature $T_{0}=2.2 \times 10^{3}$K. A rectangular tab was located at the exit of the nozzle, and four geometric parameters of the tab were defined as shown in Figures 3(b)-(d). $h$ is the tab insertion height, $d$ is the width, $x$ is the axial position, and $\beta$ is the incline angle. This paper will study the influence of these four geometric parameters on the thrust vector nozzle separately.
5. Result analysis

5.1. Influence of tab insertion height
Nozzle with tabs of \( h = 2, 4, 6, 8, 10 \) mm were numerically simulated, and other three parameters \( d = 10 \) mm, \( x = 0 \) mm, \( \beta = 0^\circ \) remained unchanged. The Mach number contours of the nozzle symmetry plane are shown in Figure 4 at different tab insertion heights. When \( h = 2 \) mm, because the tab blocked the flow of fluid near the wall of the nozzle, the boundary layer separation phenomenon occurred upstream of the tab, and a wedge-shaped separation zone was generated, thereby deflecting the main stream, generating a thrust vector, and inducing an oblique shock wave at the separation point. As the insertion height increased, the separation point gradually moves forward while creating a bow shock at the top of the tab. When \( h = 10 \) mm, the bow shock at the top of the tab had extended to the nozzle axis. The combined action of the oblique shock wave and the bow shock wave caused the thrust loss of the nozzle. The thrust vector characteristic curves are shown in Figure 5. Both the lateral force coefficient and the thrust loss coefficient increased as the tab insertion height increased. The thrust vector efficiency decreased as the insertion height increased, as shown in Figure 6. \( \eta = 5.02 \) when \( h = 2 \) mm, and \( \eta = 1.27 \) when \( h = 10 \) mm. This is because as the height of the tab insertion increased, the extension height of the oblique shock wave and the bow shock wave increased, but the bow shock wave grown faster, and the thrust loss caused by the bow shock was gradually enhanced. Therefore, increasing the tab insertion height can improve the lateral control force, but at the same time reduce the control efficiency.

![Mach number contour in symmetry plane](image1)

![Thrust vector performance curves](image2)

![Thrust vector efficiency curve](image3)
5.2. Influence of tab width
Nozzle with tabs of $d=10, 12, 14, 16, 18$ mm were numerically simulated, and other three parameters $h=10$ mm, $x=0$ mm, $\beta=0^\circ$ remained unchanged.

The nozzle wall surface and outlet cross-section pressure contour corresponding to the tabs of different widths are shown in Figure 7, $p$ is the local static pressure and $p_0$ is the total inlet pressure of the nozzle. As the width of the tab increased, the range of the high pressure zone on the wall of the nozzle became wider, and the separation point of the boundary layer moved forward. The thrust vector performance curves are shown in Figure 8. The lateral force coefficient of the nozzle increased with the increase of the tab width, $C_S=9.0\%$ when $d=10$ mm, and $C_S=13.4\%$ when $d=18$ mm. The thrust loss coefficient changed little with the increase of tab width, $C_A=5.8\%$ when $d=10$ mm and $C_A=7.0\%$ when $d=18$ mm. The thrust vector efficiency curve is shown in Figure 9. As the width of the tab increased, $\eta = 1.53$ for $d = 10$ mm, $\eta = 1.91$ for $d = 18$ mm, and the thrust vector efficiency was increased by 24.8%. Increasing the width of the tab can improve the control efficiency while improving the lateral control force, which is an effective optimization method.

5.3. Influence of tab axial position
Nozzle with tabs of $x=0, 0.5, 1, 1.5, 2$ mm were numerically simulated, and other three parameters $h=10$ mm, $d=10$ mm, $\beta=0^\circ$ remained unchanged.

The symmetry plane streamline distribution of nozzle with tabs at different axial positions are shown in Figure 10. It can be seen that when $x=0$, there was a significant back flow zone upstream of the tab. When $x=1$ mm, a part of the gas leaked from the gap between the tab and the nozzle, and the boundary layer separation point moves backward, and the back flow zone became smaller. When $x=2$ mm, the bow shock upstream of the tab moves back to the nozzle outlet, and the interaction between bow shock and the boundary layer of the nozzle wall was very weak, and the back flow zone was no longer formed. The pressure curves of the lower wall of the nozzle with tabs at different axial positions are shown in Figure 11. The pressure distribution generally rose first, then fell, and finally rose and peaked. The first pressure rise point was the boundary layer separation point, and the second pressure rise position corresponded to the position of the bow shock wave. It can be seen in the figure that the boundary layer separation point and the bow shock wave was shifted back as the axial position of the tab increased. The thrust vector performance curves are shown in Figure 12. Due to the gas leakage, the lateral force coefficient of the nozzle dropped sharply with the increase of the axial position of the tab, $C_S=9.0\%$ when $x=0$ mm, and $C_S=1\%$ when $x=2$ mm. The thrust loss coefficient increased first and then decreased with the increase of the axial position of the tab. The thrust vector efficiency curve is as shown in Figure 13, and decreased sharply as the axial position increased, $\eta=1.54$ for $x=0$ mm and $\eta=0.1$ for $x=2$ mm. Increasing the axial...
position of the tab reduces the lateral control force and reduces the control efficiency. Therefore, the gap between the tab and the nozzle outlet should be minimized in practical applications.

5.4. Influence of tab incline angle
Nozzle with tabs of $\beta=0^\circ$, 5$^\circ$, 10$^\circ$, 20$^\circ$, 30$^\circ$, 40$^\circ$ were numerically simulated, and other three parameters $h=10\text{mm}$, $d=10\text{mm}$, $x=0\text{mm}$ remained unchanged.

The symmetry plane Mach number contours corresponding to different tab incline angles are shown in Figure 14. As the incline angle increased, the boundary layer separation point and the position of the bow shock wave move backward, the oblique shock wave extension height decreased, the back flow zone range decreased, and the extension height of the bow shock wave increased. The thrust vector performance curves are shown in Figure 15. Lateral force coefficient changed slightly with the incline angle. $C_S=9.8\%$ at $\beta=0^\circ$, peak at $\beta=5^\circ$, $C_S=10.0\%$, and $C_S=8.7\%$ at $\beta=40^\circ$. The thrust loss coefficient increased first and then decreased with the increase of incline angle. When $\beta=0^\circ$, $C_\Delta = 6.4\%$, when $\beta=10^\circ$, the peak value was reached, $C_\Delta = 9.7\%$, and when $\beta=40^\circ$, $C_\Delta = 7.7\%$. The thrust vector efficiency curve is shown in Figure 16. As the incline angle increased, thrust vector efficiency first decreased and then rose. When $\beta=0^\circ$, the efficiency was the highest, $\eta=1.52$, and when $\beta=20^\circ$, the efficiency was the lowest, $\eta=0.99$. 

![Figure 14. Mach number contour in symmetry plane](image_url)

![Figure 10. Contour of Mach number and streamline in symmetry plane](image_url)

![Figure 11. Pressure distribution at the nozzle wall](image_url)

![Figure 12. Thrust vector performance curves](image_url)

![Figure 13. Thrust vector efficiency curve](image_url)
6. Conclusion

In order to meet the requirements of control rate modeling and optimization of jet tab thrust vector control system, a computational study was conducted to investigate the effects of tab geometric parameters which include insertion height, width, axial distance, tilt angle on nozzle aerodynamic characteristics. The flow structure of nozzle with different tabs are demonstrated, and thrust vector performance is evaluated. The result indicate that the insertion height, width, axial position and incline angle of the tab, these geometric parameters will have non-negligible influence on the performance of the thrust vector nozzle, attention should be paid on those parameters in the design and optimization of the tab. The lateral force coefficient and the thrust loss coefficient increased with the increase of the tab insertion height, the thrust vector efficiency decreased as the insertion height increased. Increasing the width of the tab will increase the thrust vector efficiency while increasing the lateral force coefficient. As the width of the tab increased from 10 mm to 18 mm, the thrust vector efficiency was increased by 24.8%. The increase of the tab axial position and the incline angle will decrease the lateral force and thrust vector efficiency. In practical application, the axial position and incline angle should be minimized.

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