Analysis of Thrust Vectoring Nozzle with a Secondary Shock Wave Channel

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Abstract. A two-dimensional fluidic thrust vectoring nozzle with a secondary shock wave channel is designed in this paper. The direct secondary shock wave channel is composed of a front vacuum chamber, a secondary flow chamber, and a rear vacuum chamber. Based on the numerical simulations using a Navier-stokes solver, the structural parameters of the secondary shock wave channel on the nozzle performance are studied.

1. Introduction
By deflecting the jet flow out of the engine tail to modify the thrust component, thrust vectoring technology supplements or replaces the aerodynamic forces on conventional flight control surfaces [1-2]. However, a large number of mechanical moving parts and wall structures make the system more complex, less reliable and short the engine service life [3]. Shock vector control technology, is a form of fluidic thrust vectoring, which injects a secondary flow into the expansion section of the nozzle.

In the present study, the research on shock vector control methods relies on theoretical analysis, numerical simulations and nozzle model experiments. Silnikov et al. theoretically analyzed a wide range of governing flow parameters in planar over expanded jet flow, and investigated flow vorticity parameters in post shock flow [4]. Deng et al. changed the pressure of the axisymmetric revolving nozzle and analyzed the instability of the boundary layer. It was found that different nozzle pressure ratio (NPR) greatly affected the boundary layer variation [5]. Zmijanovic et al. investigated an axisymmetric conical supersonic nozzle with thrust-pitching angle versus mass flow rate ratio with a large NPR [6]. Because the secondary flow is the key to improving the nozzle performance and increasing efficiency, the design and control of the secondary flow is very important. In this paper, a two-dimensional thrust vectoring nozzle with a secondary shock wave channel is proposed.

2. Nozzle configuration
2.1 Main nozzle geometric model and design parameters
A schematic diagram of a two-dimensional converging-diverging nozzle with an incident oblique shock wave flow is shown in Figure 1. The upper and lower walls of the inlet section are circular arc surfaces, the expansion section is composed of planes, and the arc surfaces of the inlet section are tangent to the planes of the expansion section at the nozzle throat [7]. Region ‘A’ represents the range of the secondary shock wave channel.
2.2 Configuration model of vertical secondary shock wave channel

In order to improve the secondary flow efficiently, a secondary shock wave channel is designed. The channel structure is composed of three parts: a front vacuum chamber, a secondary flow chamber, and a rear vacuum chamber. Figure 2 is an enlarged view of the secondary flow channel, corresponding to the region indicated by 'A' in Figure 1.

3. Numerical model and performance calculation

The numerical calculation fits the mass conservation equation, the momentum conservation equation and the energy conservation equation [8].

The thrust pitching angle \(\delta_p\) is an important parameter for evaluating the performance of the nozzle.

\[
F_x = \sum (\rho u^2 + (p - p_e)) \cdot \Delta A
\]  

(1)
\[ F_y = \sum (\rho uv) \cdot \Delta A \]  
\[ \delta_p = \tan^{-1}(F_y / F_x) \]  

4. Nozzle performance analysis

Based on the simulation results, the pre-optimized model with superior thrust vector performance selected in multiple schemes is investigated. The effects of the nozzle configuration in a defined range on the secondary shock wave and thrust pitching angle \( \delta_p \) are analyzed.

4.1 The effect of \( e \) on \( \delta_p \)

The variable \( e \) is the distance from the secondary shock wave channel to the nozzle outlet. The relationship between \( e \) and \( \delta_p \) at \( e = 11—20 \text{ mm} \) is shown in Figure 3.

As \( e \) increases, \( \delta_p \) shows a downward trend and eventually becomes negative value. The reason for this trend is that when the secondary flow channel is too close to the nozzle throat, the secondary flow is reflected toward the opposite lower wall of the nozzle, which weakens the flow direction of the main flow. When the distance between the secondary flow channel and the nozzle outlet is small, the pressure difference between the upper and lower wall of the main nozzle increases, which results in a large thrust pitching moment where the throat acts a moment center.

4.2 The effect of \( \delta_1 \) on \( \delta_p \)

The variable \( \delta_1 \) is the wedge wall angle of the secondary flow chamber. The relationship between \( \delta_1 \) and \( \delta_p \) with \( \delta_1 \) in the range of \( 16^\circ—30^\circ \) is shown in Figure 4.
4.4 The effect of γ on δ_p
The variable γ is the deflection angle of the inclined wall of the secondary flow chamber. The relationship between γ and δ_p with γ in the range of 45°—60° is shown in Figure 6.
The $\delta_p$ reaches a local maximum value of 16.2° at $\gamma = 45^\circ$ and a minimum local value of 12.8° at $\gamma = 60^\circ$. As $\gamma$ increases, the lower portion of the secondary flow chamber is enlarged, the local compression in the high-speed flow is weakened and the shock intensity is decreased, which results in a downward trend of $\delta_p$. When $\gamma$ is in the range of 55°—60°, the region around the inclined wall of the secondary flow chamber becomes smaller, which strengthens the suppressing effect on the secondary flow.

5. Conclusions
Based on the thrust vector control principle and the shock mechanism, a two-dimensional converging and diverging nozzle with a secondary shock wave channel is proposed. The secondary flow channel is designed with a front vacuum chamber, a secondary flow chamber, and a rear vacuum chamber. The simulation results suggest that the direct secondary shock wave channel is effective in increasing the efficiency of the secondary flow and improving the nozzle performance.

Based on the numerical simulations, the effects of channel geometric parameters on the thrust pitching angle are studied. The effect of $e$ on $\delta_p$ is notably larger than others shock parameters, such as $\delta_1$, $w_1$ and $\gamma$.

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