Study on the Aerodynamic Characteristics of Top-Mounted Inlet with Different Lip Angles

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Abstract. The stealthy performance is an important factor to be considered in the design of the modern UAV, and the inlet is the strong RCS scattering source, which needs to be paid more attention. The inlet with lip angle is beneficial to the stealth performance, but unfavorable to the aerodynamic characteristics of the inlet. In this paper, three inlets with different lip angles are studied, and the characteristics of the inlets are obtained by using CFD and experimental methods. Results indicate: 1) data obtained by CFD well predicts the vortex in the inlet, and it’s very close to the experimental value, which shows that CFD method can be used for analysis; 2) the lip angle has a great influence on the characteristics of the inlet under ground running, and the circumferential distortion index of the inlet increases rapidly with the increase of the lip angle; 3) the effects of the lip angle on the characteristics of the inlet can be ignored under the condition of the high incoming Mach number.

1. Introduction
The design of modern UAV (Unmanned Aerial Vehicle) is often need to consider the stealth performance, and the inlet is one of the UAV radar wave strong scattering sources, so the design of the inlet must consider stealth performance [1-3]. In order to improve the stealth performance of the inlet, the common methods are as follows: Diverterless supersonic inlet is often used to improve the stealth performance for the boundary layer from the fuselage pushing away by designing the bump surface and it can reduce the radar scattering area, the weight of the structure and the aerodynamic resistance [4-5]. Serpentine inlet is designed to fully block the engine compressor blades with large blend surface of its own [1, 6-7]. However, the flow control technology including active flow control, passive flow control and hybrid flow control often needs to be considered in the serpentine inlet due to the drastic changes in the internal duct [8-12]. One more, submerged inlet is applied to eliminate the adverse effect of the inlet on stealth performance, but the total pressure recovery of the submerged inlet is not large [13]. In this paper, the aerodynamic characteristics of the inlets with three different lip angles are given by CFD and experimental methods, and the reasons for circumferential distortion index of the inlets with different lip angles are analyzed.

2. Geometric Model and numerical method
Figure 1 shows the research object of this paper, which is a conventional top-mounted inlet with different lip angles of 0°, 10° and 20°, so as to study the influence of different lip angles on the aerodynamic characteristics of the inlet. The half physical model is used for simulation research since the influence...
of sideslip angle is not involved. Multi-block structure meshes are generated by using ICEM CFD software, the simulation domain is set to $50l \times 30l \times 30l$ ($l$ is the characteristic length of the model), and the elements of half model is approximately 6 million. Figure 2 shows the mesh for the lip. The numerical analysis is carried out by adopting the Reynolds-averaged Navier-Stokes equations and $k-\omega$ SST turbulence model.

![Fig. 1 Diagrammatic sketches of the inlet with different lip angles](image1)

Fig. 1 Diagrammatic sketches of the inlet with different lip angles

![Fig. 2 Mesh for the lip](image2)

Fig. 2 Mesh for the lip

3. Experimental Test
Wind tunnel scaling test is carried out on the model with the lip angle $\gamma=0^\circ$, and the blockage of the model to the test section of the wind tunnel at $\alpha=0^\circ$ is 0.36%. In the measuring section of the test model, there are 40 total pressure probes, 8 static wall pressure taps and 3 dynamic pressure transducers distributed in an equal-area loop to measure the airflow parameters at the AIP (aerodynamic interface plane), as shown in figure 3.

![Fig. 3 Test rake at the AIP](image3)

Fig. 3 Test rake at the AIP
4. Results and Discussion

4.1. Experimental and CFD results
Mass flow ratio is defined as \( \varphi = q(\lambda) \cdot \cdot A_{\text{out}} / A_{\text{th}} \), in which, \( q(\lambda) \) represents the aerodynamic function corresponding to the area-average Mach number at the AIP, \( \sigma \) represents the total pressure recovery at the AIP, and \( A_{\text{out}} / A_{\text{th}} \) represents the ratio of the AIP area to the throat area. Figure 4 shows the variation of the total pressure recovery obtained by CFD and experimental method with mass flow ratio at \( \gamma = 0^\circ \), \( \text{Ma}=0.01 \). Figure 5 shows the total pressure contours obtained by CFD and experimental method at the AIP with \( \varphi = 0.815 \). It can be seen that the results obtained by the CFD method adopted in this paper are basically consistent with the experimental values, and the total pressure recovery has a consistent trend of decreasing with the increase of the mass flow ratio. Meanwhile, by observing Figure 5, it can be seen that compared with the experimental values, the regions of high total pressure and low total pressure obtained by CFD are very close to the experimental results. Therefore, the following analysis is based on the CFD results.

Fig. 4 Total pressure recovery versus mass flow ratio (Ma=0.01)

Fig. 5 Total pressure contours at the AIP (\( \varphi = 0.815 \))
4.2. Effects of different lip angle

Figure 6 shows the variations of the total pressure recovery and circumferential distortion index at the AIP with mass flow ratio under the conditions of incoming $Ma=0.01$, $\gamma=0^\circ$, $\gamma=10^\circ$, and $\gamma=20^\circ$. Figure 7 shows the total pressure contours versus mass flow ratio at the AIP. It is obvious that the total pressure recovery of the inlet presents a decreasing trend with the increase of the mass flow rate, and the distortion basically presents an increasing trend. The total pressure recovery of $\gamma=0^\circ$ is greater than that of $\gamma=10^\circ$, and the total pressure recovery of $\gamma=10^\circ$ is greater than that of $\gamma=20^\circ$, but the circumferential distortion of $\gamma=0^\circ$ is almost the same as that of $\gamma=10^\circ$, while the circumferential distortion of $\gamma=20^\circ$ increases faster with mass flow rate.

Figure 8 shows the total pressure recovery contours at different sections of the inlet under the conditions of incoming $Ma=0.01$, $\gamma=0^\circ$, $\gamma=10^\circ$, and $\gamma=20^\circ$. Combined with figure 7, when $\gamma=0^\circ$, the generation of a pair of vortex at the AIP is mainly due to the low energy flow in the boundary layer on the lower wall of the inlet under the typical action of the S-shaped inlet, a pair of vortex (lower total pressure recovery region) is finally generated as shown in figure 7(a). The region of the upper low total pressure recovery is mainly caused by the normal development of the low energy flow in the boundary layer in the inlet duct. As the lip angle increases to $\gamma=10^\circ$, the low energy flow in the boundary layer on the lower wall of the inlet still develops to a pair of vortex, differently, due to the increase of windward area, which leads to the change of the air flow into the inlet of the circulation area, that makes the entrainment vortex occurs on the upper surface of the inlet, and with the increase of mass flow rate, the intensity of the vortex rises as shown in figure 7 (b), finally. When lip angle further increases to $\gamma=20^\circ$, the intensity of the vortex becomes greater, this strong vortex compresses the region of high total pressure downward, it is the reason that the region of the lower total pressure at the lower of the AIP, however, at this time, the upper lower pressure region at the AIP is large, the circumferential distortion exceeds the allowable value, and usually, flow control technology is needed.
Figure 7 shows the variations of the total pressure recovery and circumferential distortion index at the AIP with mass flow ratio under the conditions of incoming Ma=0.8, γ=0°, γ=10°, and γ=20°. It can be seen that with the increase of mass flow rate, the total pressure recovery decreases and the circumferential distortion index increases, the influence of lip angle can be almost ignored. Combined with figure 10, the low total pressure in the inlet duct is mainly caused by the low energy flow in the boundary layer, and it’s typical a pair of vortex distribution.
Figure 9 shows total pressure recovery and circumferential distortion index versus angle of attack under the condition of $Ma=0.8$, $\alpha=0^\circ$, $\gamma=20^\circ$, $\varphi=0.94$. It can be seen that with the increase of angle of attack, more low energy flow in the boundary layer from the fuselage flows into the inlet, resulting the lower total pressure recovery and a larger circumferential distortion index.

Figure 10 shows total pressure recovery contours at different sections of the inlet ($Ma=0.8$, $\alpha=0^\circ$, $\gamma=20^\circ$)
Fig. 11 Total pressure recovery and circumferential distortion index versus angle of attack (Ma=0.8)

5. Conclusion
Lip angle has a great impact on the aerodynamic characteristics of the inlet under ground running, and the circumferential distortion index of the inlet increases rapidly with the increase of the lip angle for the vortex generated in the inlet lip becoming stronger. When the lip angle further increases to $\gamma=20^\circ$, the circumferential distortion index of the inlet is not acceptable, and usually, flow control technology is needed. As the incoming Mach number increases, effects of lip angle on the aerodynamic characteristics of the inlet become smaller, for instance, Ma=0.8 mentioned in this paper, the effects can be ignored.

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