Numerical Investigation of the Inlet with Different Lip-plane Shapes under Ground Running

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Abstract. The inlet of the UAV is usually designed on the back of the aircraft in order to give consideration to the overall arrangement and stealth performance. Under ground running, there are often severe vortices in the duct of the backpack inlet, which leads to low total pressure recovery and large circumferential distortion index at the AIP. Different shapes of the lip-plane produce different vortices, which have great impact on circumferential distortion index at the AIP. In this paper, the characteristics of three different lip-plane shapes were studied under the ground running. Results indicate: (1) W-shaped inlet has lowest circumferential distortion index and the flow distribution is the most uniform at the AIP; (2) Λ-shaped inlet has the weakest of the vortex strength and the largest total pressure recovery, which means the thrust loss caused by the inlet is smallest; (3) V-shaped inlet has the strongest vortex strength and the lowest total pressure recovery.

1. Introduction
The inlet is an important component to provide stable and high quality airflow to the engine, and the aerodynamic characteristics of the inlet have a significant impact on the working efficiency and stability of the engine [1]. Under ground running, the aerodynamic characteristics of the inlet are relatively poor because the flow separation in the inlet is serious, by this time, the performance of the inlet can meet the distortion requirement of the engine is the key point to be considered in the design of the inlet. Many researchers have studied the characteristics of the inlet under ground running, JING studied the influence of boundary layer suction on the characteristics of the serpentine inlet under ground running through experiments, and the results show that the total pressure recovery of the inlet is improved and the circumferential distortion index is decreased after boundary layer suction [2]. HUA obtained the influence of swept-back lip on aerodynamic characteristics of binary hypersonic inlet, and came up the suggestion that swept lip can improve the starting capacity of the inlet [3]. BAI gave the aerodynamic characteristics of the inlet at the crosswind condition under ground running, and the intensity of the vortex in the inlet is determined by the combined influence of the incoming Mach number and the height from the ground [4]. The ground aerodynamic characteristics of the S-bend inlet at the abdomen were studied by WEN, as a result that the distortion of the inlet is large at the ground and high Angle of attack [5]. Moreover, the mechanism of vortex generation in the inlet have been studied a lot [6-8]. In this paper, the characteristics of three different lip-plane shapes were studied under the ground running, the phenomenon and mechanism of the inlet were given.
2. Geometric Model and Numerical Method
Due to many parameters have effects on the characteristics of the inlet, in order to facilitate research on the lip-plane shape on the performance of the inlet, three inlets were generated by CATIA software. Except for the different lip-plane shapes, the other parameters of the inlets are the same. Figure 1 shows the diagrammatic sketches of the inlet with different lip-plane shapes.

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

Multi-block structure meshes were generated by using ICEM CFD 17.2 software. Figure 2 shows the mesh for the flow field of the inlet. The simulation domain is set to 300D×40D×50D. D is the diameter of the AIP (Aerodynamic interface plane). Half model with approximately 7 million elements was used for the numerical simulation. The numerical analysis was carried out by adopting the Reynolds-averaged Navier-Stokes equations and k-ω SST turbulence model [9-10].

The working conditions of the inlets studied in this paper are all under ground running, and the Mach number of the AIP is 0.5.

![Fig. 2 Mesh for the flow field of the inlet](image2)

3. Results and Discussion

3.1. Phenomenon
Figure 3 shows the total pressure recovery contours and the streamlines of the inlets with different lip-plane shapes. It can be seen that there are large vortices at the lips of the three different lip-plane inlets, but the initial locations in the three inlet ducts are quite different as shown in figure 4. With the further development of the flow, the large ranges of flow separation appear in the inlets, and the distributions of the total pressure recovery is very uneven at the AIP.
Figure 3 shows the total pressure recovery contours and the streamlines of the inlets with different lip-plane shapes. Figure 4 shows the streamlines near the lips of the inlets with different lip-plane shapes.

Figure 5 shows the vorticity magnitude contours near the lips of the inlets with different lip-plane shapes. Figure 6 shows the total pressure recovery contours of the inlets with different lip-plane shapes at the AIP. Table 1 gives the aerodynamic characteristics of the inlets with different lip-plane shapes at the AIP. It can be seen that the total pressure recovery of the inlet with V-shaped lip is smaller than the inlet with W-shaped lip, and the total pressure recovery of the inlet with W-shaped lip is smaller than the inlet with Λ-shaped lip. The intensity of vortices generated by the V-shaped lip is much stronger than that of the other two, and the value of low total pressure recovery is also much smaller than that of the other two. The inlet with the W-shaped lip has lowest circumferential distortion index and the flow distribution is the most uniform at the AIP, as shown in figure 6(a). The inlet with the Λ-shaped lip has the weakest of the vortex strength and the largest total pressure recovery, which means the thrust loss caused by the inlet is smallest.

At the same time, we can see that no matter what kind of the inlet lip-plane shape, a pair of classical counter vortices appear at the AIP, but the distribution and the strength are different. This shows that
the inlet lip-plane shape can only change the strength and position of the vortex, but cannot inhibit the vortex generation under ground running.

![Vorticity magnitude contours near the lips of the inlets with different lip-plane shapes.](image)

**Fig. 5** Vorticity magnitude contours near the lips of the inlets with different lip-plane shapes.

![Total pressure recovery contours of the inlets with different lip-plane shapes at the AIP.](image)

**Fig. 6** Total pressure recovery contours of the inlets with different lip-plane shapes at the AIP.

**Table 1.** Aerodynamic characteristics of inlet with different lip-plane shapes at the AIP.

|          | W-shaped | Λ-shaped | V-shaped |
|----------|----------|----------|----------|
| σ        | 0.9502   | 0.9556   | 0.9425   |
| Δσ/σ₀    | 1.19%    | 3.64%    | 3.34%    |

3.2. Mechanism

This paper takes the inlet with the V-shaped lip as the research object to do further research on the mechanism. Figure 7 shows the streamlines and Mach number distribution of the symmetric plane (V-shaped). The flow coefficient is much greater than 1 when the inlet is under ground running. At this time, the local flow at the lip of the inlet is similar to the state of high angle of attack, the aerodynamic cross section of the inlet is compressed, the local Mach number distribution is further uneven, and the flow separation occurs under the strong adverse pressure gradient.
Figure 7 Streamlines and Mach number distribution of the symmetric plane (V-shaped).

Figure 8 shows the streamlines and the pressure distribution near the lip of the inlet. Figure 9 shows the vortex lines near the lip of the inlet. It is observed that the pressure gradient near the lip is large and unevenly distributed along the spreading direction. The pressure is minimum near the corner of the V-shaped lip which indicates the surface streamlines flow to the corner. In addition to the vortex lines in figure 9, we can know the lip is similar to the edge of the fuselage, and the generated strake vortexes converge towards the corner of the lip, where the intensity of the vortices is the strongest.

Figure 8 Streamlines and the pressure distribution near the lip.
4. Conclusion

The ground running state of the UAV cannot be ignored, and the aerodynamic characteristics of the inlet under ground running are often the worst. Different lip-plane shapes have great impact on the distribution and the strength of the vortex. The lip is similar to the edge of the fuselage, and the generated strake vortexes converge towards the corner of the lip, where the intensity of the vortices is the strongest, which causes the results that V-shaped inlet has the strongest vortex strength, W-shaped inlet has lowest circumferential distortion index and A-shaped inlet has the largest total pressure recovery.

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