Hybrid Flow Control on Boundary Layer Ingestion Inlet

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Abstract. For the boundary layer ingestion (BLI) inlet, how to control the flow is very important to improve the quality of the air flow at the outlet. In this paper, the research on the passive flow control is carried out by using rectangular straight spoiler blades, and the active flow control is carried out by using the blowing pipes. Finally, the effect of hybrid flow control is explored by combining the passive flow control device and the active flow control device. The results show that the spoiler blades can squeeze the low pressure zone to both sides of the outlet and reduce the area of the low pressure zone. The steady-state circumferential distortion coefficient of the outlet can be reduced by 66.7% by adopting the appropriate passive flow control scheme. The blowing rate of active flow control has a significant effect on the flow control effect. The optimal hybrid flow control scheme is obtained by optimization and the steady-state circumferential distortion coefficient can be reduced by 76.8% when the blowing flow rate is 0.67% of the inlet flow.

1. Introduction
To deal with environmental problems and develop revolutionary propulsion technologies, NASA launched UEET (Ultra Efficient Engine Technology) Technology project in late 1999, and part of the project is to explore the possibility of blended wing body (BWB) integration flight [1]. BWB aircraft can have a variety of structures [2-5]. The inlet is usually installed on the back of the aircraft and is designed with no partition, which will inevitably intake the boundary layer, thus increasing the distortion of the outlet and reducing the total pressure recovery coefficient [6]. Therefore, it is very important to improve the quality of the outlet flow by proper flow control.

There are many researches on the flow control of BLI inlet at home and abroad. Anabtawi et al. [7-10] used spoiler blades to control the BLI inlet effectively. Tormalm [11] studied the effect of blowing speed on flow control. The results show that the larger the blowing speed is, the more obvious the distortion decreases. Allan et al. [12] optimized the number of blowing holes, installation position and blowing volume, and the total pressure distortion coefficient DC (60) was reduced by about 64%. Gissen et al. [13] fuses the spoiler blades and the synthetic jet together on the basis of the existing control device, and the results show that the effect of hybrid flow control is better than that of single flow control, but a complete flow control scheme has not been formed.

Judging from the existing research results, the current researches on BLI inlet flow control mostly use a single flow control scheme, and achieve better control effect by changing the geometry, installation position and installation angle of the flow control device. Passive flow control can only play a good effect at the design point, and the flow control effect is not obvious in other working conditions. Active flow control needs to arrange more blowing and suction pipes and provide a large amount of blowing
and suction to achieve obvious flow control effect. In order to balance the advantages and disadvantages of the two, we can try to combine the two flow control devices to effectively reduce the total pressure distortion with less energy injection.

In this paper, hybrid flow control is carried out for a BLI inlet. Spoiler blades are chosen as passive flow control device, and blowing pipes are chosen as active flow control device. Based on the study of single flow control effect, the two flow control devices are integrated to explore the effect of the hybrid flow control.

2. Physical model and numerical method

2.1. Physical model

The hybrid flow control model of the BLI inlet studied in this paper is shown in Fig. 1. Due to the symmetry of the inlet model, half of the model is selected for calculation. In order to better simulate the flow field, CFD extensions are arranged before the entrance and after the exit of the inlet. According to the need, some flow control devices can be arranged in the inlet. The passive flow control device are spoiler blades, and the active flow control device are cylindrical pipes with a diameter of 10 mm.

![Figure 1. Hybrid flow control model of S-shaped inlet.](image)

2.2. Numerical method

In this paper, the commercial software ICEM is used to generate structured grids for the BLI inlet model. Fig. 2 shows the grid of the hybrid flow control device. CFX solver and SST model are used in the calculation. The calculation condition is that the flying height is 13km, and the flying Mach number is 0.5. The thickness of the boundary layer is 30% of the inlet height, which is given by the total pressure step function. The total pressure distribution at the entrance of the inlet is shown in Fig. 3. The static pressure boundary is given at the outlet and the smooth and non slip wall boundary conditions are adopted at the inlet wall, the spoiler blades and the blowing pipes.

![Figure 2. Grid of hybrid flow control model.](image)
3. Performance analysis of inlet without flow control

Fig. 4 shows the total pressure recovery coefficient contours of the along-pass sections without flow control and Fig. 5 shows the total pressure recovery contour of outlet without flow control. It can be seen that the boundary layer gradually thickens along the way, and the low energy flow converges at the lower part of the outlet, forming a large area of low total pressure region. Fig. 6 shows the streamlines at bottom of the inlet without flow control. It can be seen that the streamlines finally converges at the bottom of the outlet. Fig. 7 shows the velocity vector diagram of symmetry plane without flow control. Flow separation occurs in the middle of the lower wall. The total pressure recovery coefficient is 0.9656 and the steady-state circumferential distortion coefficient is 8.30%. Therefore, it is necessary to control the flow of the BLI inlet.
4. **Effect analysis of single flow control**

4.1. **Effect analysis of the independent passive flow control**

For passive flow control, the flow field distribution of the inlet is observed by changing the axial installation position, installation angle, blade number and the height of the blades. Fig. 8 shows passive flow control device at different axial positions.

Fig. 9 shows the streamlines near the spoiler blade. It can be seen that there is an angle between the spoiler blade and the main stream, and the flow separation occurs after passing through the spoiler blade, which creates a vortex. The vortex makes the high momentum fluid in the main stream exchange with the low momentum fluid in the boundary layer, so as to inject the high momentum fluid into the boundary layer.

Through the optimization of the passive flow control device, the best passive flow control scheme is obtained, that is, the passive flow control device is arranged at 450mm upstream of the separation point, the blade height is 20mm, the installation angle is $15^\circ$ and the number of blades is 5. Fig. 10 shows the total pressure recovery coefficient contours of inlet sections and outlet under optimal passive flow control scheme. It can be seen that the boundary layer at the bottom of the inlet is gradually squeezed to both sides, and the total pressure distribution at the outlet is uniform. For this passive flow control scheme, the total pressure recovery coefficient is 0.9676 and the steady-state circumferential distortion coefficient is 2.76%. Compared with the case without flow control, the steady-state circumferential distortion coefficient is reduced by 66.7%.
4.2. Effect analysis of single active flow control
For active flow control, the flow field distribution of the inlet is observed by changing the axial installation position, blowing angle, pipe number and the blowing rate of the pipes.

Fig. 11 shows the streamlines near the pipe. There is a certain angle between the blowing direction and the main flow. The blowing flow is coupled with the internal flow of the inlet, which drives the high momentum fluid in the main flow to exchange with the low momentum fluid in the boundary layer.

The effect of blowing rate on active flow control is significant. Five blowing tubes are arranged on half of the inlet model, and the blowing angle is 30°. Fig. 12 shows the total pressure recovery coefficient contours of the inlet under different blowing rate. Table 1 shows the total pressure recovery coefficient and the steady-state circumferential distortion coefficient under different blowing rate. It can be seen that with the increase of blowing rate, the total pressure distribution at the outlet becomes more uniform and the flow control effect is better.

Figure 10. Total pressure recovery coefficient contours of inlet sections and outlet under optimal passive flow control scheme.
5. Effect analysis of hybrid flow control

5.1. Preliminary exploration of hybrid flow control

According to the previous exploration of single flow control, the blade of passive flow control is installed at 450 mm upstream of separation point, the blade height is 20 mm and the installation angle is 15 degrees. The blowing angle of active flow control is 45 degrees.

Fig. 13 shows the streamlines near the hybrid flow control device. We can see that the passive flow control device generates vortex, and the active flow control device injects energy to impose disturbance mode. The two together with the mainstream drive the momentum exchange between high momentum fluid and low momentum fluid.

Firstly the active flow control device is installed at 375 mm upstream of the separation point. The results show that the total pressure recovery coefficient is 0.9639, the steady-state distortion index is 2.13%, and the blowing volume is 0.83%. Fig. 14 shows the total pressure recovery coefficient contour and streamlines. It can be seen that the streamlines at the bottom of the inlet deflect obviously to both sides, and the low pressure region at the outlet also distributes on both sides. However, there is still a small low pressure area at the bottom of the outlet. By analyzing the characteristics of the flow field along the cross section, it is considered that the flow control device near the symmetry plane is far away from the symmetry plane, and the vortex can not fully drive the low energy flow at the symmetry plane.
Figure 14. Total pressure recovery coefficient contour and streamlines when 5 blowing pipes are installed at 375mm upstream of separation point.

5.2. Effect analysis of adding flow control device at the bottom near the symmetry plane of inlet
For passive flow control devices, add a spoiler blade close to the symmetry plane. Fig. 15 shows the total pressure recovery coefficient contour of the inlet after adding a spoiler blade. It can be seen that the low pressure area at the bottom of the outlet has disappeared. In the following hybrid flow control study, 6 spoiler blades are used.

Figure 15. Total pressure recovery coefficient contour of the inlet after adding a spoiler blade.

5.3. Optimization of hybrid flow control scheme
Through the preliminary exploration of hybrid flow control, the analysis of flow field found that it is necessary to set up a flow control device near the downstream. The arrangement of passive flow control remains unchanged, and the flowing pipes are arranged at 40mm downstream of the separation point. Optimize the hybrid flow control scheme by controlling the circumferential position and number of pipes.

Fig. 16 shows total pressure recovery coefficient contour and streamlines of the inlet with passive flow control device. It can be seen that the streamlines at the bottom of the inlet converge on both sides of the outlet, and there are low pressure areas on both sides.
There are four hybrid flow control schemes, as shown below:

a) Six turbulence blades are arranged at 450mm upstream of the separation point, and eleven blowing tubes are arranged at 40mm downstream of the separation point. Fig. 17 shows the total pressure recovery coefficient contour and streamlines. It can be seen that the total pressure distribution at the outlet is very uniform.

b) Six turbulence blades are arranged at 450mm upstream of the separation point, and four blowing pipes are arranged at the bottom of the inlet 40mm downstream of the separation point. Fig. 18 shows the total pressure recovery coefficient contour and streamlines. It can be seen that there are also low pressure areas on both sides.

c) Six spoiler blades are arranged at 450mm upstream of the separation point, and four blowing pipes are arranged on the side wall of the inlet 40mm downstream of the separation point. Fig. 19 shows the total pressure recovery coefficient contour and streamlines. You can see that figure 19 and Figure 17 are similar, and the total pressure distribution is relatively uniform.
d) Six spoiler blades are arranged 450 mm upstream of the separation point, and three blowing pipes are arranged at the top of the inlet 40 mm downstream of the separation point. Fig. 20 shows the total pressure recovery coefficient contour and streamlines. It can be seen that there is a small low pressure area at the top of the inlet outlet, which is caused by the pipe blowing, and then there is still a low pressure on side wall of the inlet.

Table 2 shows the total pressure recovery coefficient and steady circumferential distortion coefficient of four hybrid flow control schemes. The results show that the steady-state circumferential distortion coefficient of scheme ‘a’ is the lowest, but the blowing rate is the largest. The steady-state circumferential distortion coefficient of scheme ‘c’ is relatively low, and the air blowing rate is much smaller than that of scheme ‘a’. Therefore, the optimal hybrid flow control scheme is scheme ‘c’. Through this scheme, the steady-state circumferential distortion coefficient is reduced by 76.9% compared with that without flow control.

Table 1. Total pressure recovery coefficient and steady circumferential distortion coefficient of four hybrid flow control schemes.

| Hybrid flow control scheme | Blowing rate | Total pressure recovery coefficient | steady-state circumferential distortion coefficient |
|----------------------------|--------------|-----------------------------------|---------------------------------------------------|
| a                          | 1.72%        | 0.9649                            | 1.73%                                             |
| b                          | 0.49%        | 0.9636                            | 2.78%                                             |
| c                          | 0.67%        | 0.9644                            | 1.92%                                             |
| d                          | 0.51%        | 0.9641                            | 2.80%                                             |

6. Conclusion
For the BLI inlet, the following conclusions can be drawn through the study of hybrid flow control.

a) The effect of hybrid flow control is better than that of single flow control;
b) When the hybrid flow control devices are arranged only at the bottom of the inlet, there are low pressure regions on both sides of the outlet, and it is difficult to further reduce the steady-state circumferential distortion coefficient.

c) By optimizing the hybrid flow control scheme, the steady-state circumferential distortion coefficient is reduced by 76.9% when the inlet blowing rate is 0.67% of inlet flow compared with that without flow control.

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