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Numerical Study on the Effectiveness of Vectoring Primary Flow with Dilator by Using Microjet Actuator

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Abstract. In the present paper, orient control of dilator primary flow in microjet were simulated numerically by using microjet actuator with the X-L whole flow field calculation model. The effects of different expansion half angles of the primary flow channel, microjet actuator amplitude, micro jet actuator frequency, and the position of micro jet actuator and primary flow velocity on deflection of primary flow were analyzed. It is found that expansion half angle has great effect on the effectiveness of vectoring primary flow with dilator using microjet actuator; if the expansion half angle is small, the wall-attached flow of micro jet plays a main role in driving the primary flow flows along dilator wall; if the expansion half angle is big enough, the coupling effect between microjet and shear layer plays the main role. With the increase of the velocity of the actuator, the controlling efficiency of microjet is expanded. Besides, dilator decreases the distance sensibility between actuator and primary flow. With the increase of primary flow velocity, the controlling efficiency of microjet is decreased.

1. Introduction
In recent years, the zero-mass jet technology dominated by microjet technology has quickly become a hotspot in the research of flow control technology, and has received widespread attention from experts and scholars at home and abroad [1~9]. The experimental and theoretical research results show that the microjet as a control system is simple, light, consumes little energy and does not require a source of work, and has high control efficiency. It initially shows the advantages that other conventional jet control methods do not have. Application prospects.

Through experimental and numerical analysis, it is found that the nozzle with the dilator, the result of the interaction between the microjet and the main stream is very different from that of the non-dilator nozzle. And the expansion half angle of the dilator, the velocity amplitude of the microjet actuator, the frequency, the position of the microjet actuator and the main speed and other parameters have a great influence on the control efficiency of the mainstream. This paper intends to conduct a numerical analysis of this situation and to explore its mechanism.

2. Control Equations and Numerical Methods
The governing equations use a two-dimensional, incompressible Faver mean N-S equation, and the turbulence model uses the SST k-ω turbulence model. The microjet actuator uses a simplified model X-L full flow field computational domain model. The second-order upwind interpolation format is used to discretize the equation space, while the time discretization uses the first-order implicit format. The discrete solver is used to iteratively solve the discrete equations. See [3] for details.
3. Calculation Model and Initial Boundary Conditions

The calculation area and grid are shown in Figure 1, and the actuator structure dimensions are shown in Figure 2 and Table 1. In order to make the parameters on the boundary change very little, the numerical anomaly will not occur, and the external flow field is 300 mm × 300 mm. The mainstream channel width H is 12 mm. The specific parameters of the main outlet are shown in Figure 2. The semi-expansion angle of the dilator is, the wall length L of the dilator is 6 mm, the actuator is placed on the wall of the dilator, and d is the central axis of the throat of the actuator and the left wall of the main channel. Distance, the central axis of the actuator is at the midpoint of the dilator wall, thus the distance of the microjet from the main flow. The actuator exit (flow center) and the wall boundary layer are mesh-encrypted.

Computational boundaries involve solid wall boundaries, free boundaries, and inlet boundaries. As shown in Figures 1 and 2, B1 is a solid wall boundary with a non-slip boundary condition, and the wall's pressure gradient and temperature gradient are zero. The B2 mobile exit is taken as a free boundary. B4 is the speed entry boundary given by the actuator simplified model X-L.

The microjet is established in a stationary ambient fluid, so the initial conditions of the flow field calculation are zero except for the B4 inlet boundary, the pressure is normal pressure, and the temperature is normal temperature. In this case, the actuator frequency f is taken as 400 Hz and the amplitude is taken as 2 mm.

4. Calculation results and analysis

4.1 Calculation conditions

The calculation conditions of the microjet actuator for the main control of the belt dilator are shown in Table 1. The mainstream speed is the velocity amplitude of the microjet vibrating film. Case0 is the basic working condition when the semi-expansion angle of the dilator is 20° and the actuator is not working. Case1 to Case8 are numerical experiments in which the microjet actuator is controlled in the mainstream when the semi-expansion angle of the dilator is different. When the microjet actuator frequency f is 400 Hz and the midpoint amplitude of the actuator film is 2 mm, the maximum velocity of the midpoint of the actuator film is $U_m = 5 m/s$. 

![Figure 1. Computational domain and grid.](image1)

![Figure 2. Partial view of the grid at the main exit.](image2)
**Table 1.** Microjet actuator mainstream vector control calculation conditions.

| Working condition | \( \gamma \) (°) | \( A_m \) (mm) | \( f \) (Hz) | \( U_m \) (m/s) | \( d \) (mm) | \( U_0 \) (m/s) |
|-------------------|----------------|--------------|-------------|----------------|-------------|-------------|
| Case0             | 20            | 0            | 0          | 0              | 1.0261      | 5           |
| Case1             | 10            | 2            | 400        | 5              | 0.5209      | 5           |
| Case2             | 20            | 2            | 400        | 5              | 1.0261      | 5           |
| Case3             | 30            | 2            | 400        | 5              | 1.5         | 5           |
| Case4             | 40            | 2            | 400        | 5              | 1.9284      | 5           |
| Case5             | 50            | 2            | 400        | 5              | 2.2981      | 5           |
| Case6             | 60            | 2            | 400        | 5              | 2.5981      | 5           |
| Case7             | 70            | 2            | 400        | 5              | 2.8191      | 5           |
| Case8             | 80            | 2            | 400        | 5              | 2.9544      | 5           |
| Case9             | 50            | 0.4          | 400        | 5              | 2.2981      | 5           |
| Case10            | 50            | 1.2          | 400        | 3              | 2.2981      | 5           |
| Case11            | 30            | 4            | 200        | 5              | 1.5         | 5           |
| Case12            | 30            | 1            | 800        | 5              | 1.5         | 5           |
| Case13            | 60            | 4            | 200        | 5              | 2.5981      | 5           |
| Case14            | 60            | 1            | 800        | 5              | 2.5981      | 5           |
| Case15            | 70            | 2            | 400        | 5              | 1.5         | 5           |
| Case16            | 70            | 2            | 400        | 5              | 5           | 5           |
| Case17            | 70            | 2            | 400        | 5              | 2.5981      | 10          |
| Case18            | 70            | 2            | 400        | 5              | 2.5981      | 15          |
| Case19            | 40            | 2            | 400        | 5              | 1.9284      | 10          |
| Case20            | 40            | 2            | 400        | 5              | 1.9284      | 15          |

4.2 The effect of expanding half-angle \( \gamma \) on the mainstream

It can be seen from Fig. 3 that the effect of different \( \gamma \) angles on the main flow of microjets is very obvious. In the case of the microjet actuator power and frequency, the microjet deflects the main stream to 40.77° at \( \gamma =30° \), and the microjet increases the deflection angle \( \phi \) of the main stream as the angle A of the dilator increases. Consistent with the Pack and Seifert experiments, the microjet achieved a maximum deflection angle of 52.63° when \( \gamma =50° \) was reached. When the angle is further increased, the \( \gamma =70° \) microjet deflects the main stream to 28.50°, and the microjet reduces the deflection angle of the main stream to not only increase but also decrease. Fig. 4(a) is a pressure diagram of the wall surface of the main channel under different A (L represents the left wall surface and R represents the right wall surface). For comparison, the formula \( y^* = y + 0.006 \cos(\gamma) \) is defined. It can be seen from Fig. 4(a) and Fig. 4(b) that when \( \gamma =50° \), the low pressure region generated between the microjet and the main flow has the greatest influence on the pressure gradient of the main channel. This is because the distance between the microjet and the main stream is small when \( \gamma =30° \), and the distance between the microjet and the main channel is larger in the y direction, which is not conducive to the upstream propagation of the low voltage region along the main channel. When \( \gamma = 70° \), the distance between the microjet and the main stream is too large, which is not conducive to the establishment of the low pressure zone. At the same time, the microjet actuator controls the main deflection efficiency. On the other hand, when the \( \gamma \) angle is less than 50°, the lower half of the dilator restricts the deflection of the main stream.
When the $\gamma$ angle is greater than 50°, as the angle A increases, the dilator provides sufficient space for the main deflection, but the wall attachment effect of the flow decreases, while the distance between the microjet and the main stream increases, the influence of the microjet on the main stream decreases, the low pressure region decreases, and the low pressure dominates the mainstream. The influence of the channel is reduced, so the control efficiency of the microjet to the mainstream is reduced.

In summary, when the $\gamma$ angle is less than 50°, the lower half of the dilator restricts the deflection of the main flow; while $\gamma$ is greater than 50°, the wall attachment effect of the microjet flow is weakened, and the distance between the microjet and the main stream is increased, and the low pressure is low. The influence of the zone on the mainstream channel is weakened, and the control efficiency of the microjet to the mainstream is reduced. Therefore, $\gamma = 50°$ is the optimum value for the semi-expansion angle in the selected operating conditions.

Case 3 ($\phi = 40.77°$)  
Case 5 ($\phi = 52.63°$)  
Case 7 ($\phi = 28.50°$)

![Figure 3. Flow field velocity contour map of mainstream vector control of different $\gamma$ angle microJet actuators.](image)

![Figure 4(a). Comparison of the pressure of the left and right wall surfaces of different $\gamma$ angles.](image)

![Figure 4(b). Comparison of lateral pressure at the joint at different $\gamma$ angles.](image)

### 4.3 Effect of actuator amplitude $U_m$ on the mainstream

Case 5, Case 9, and Case 10 simulate the effects of different speed amplitudes of microjet actuators on mainstream control. Table 2 shows that when $U_m = 5\text{m/s}$, $U_m = 1\text{m/s}$, and $U_m = 3\text{m/s}$, the frequency $f$ is 400 Hz, the mainstream speed $U_0$ is 5 m/s, and the deflection angle of the main stream
when the \( \gamma \) angle of the dilator is 50°. It can be seen from Table 2 that the larger the velocity amplitude, the higher the control efficiency of the microjet to the mainstream. On the one hand, the larger the velocity amplitude of the microjet actuator, the more fluid the microjet takes between the microjet and the mainstream in the "expiration" process due to the shearing force; the inhalation of the microjet and the mainstream in the "sucking" process. The more fluid there is, the stronger the low-pressure zone formed between the microjet and the mainstream, and the greater the influence of the low-pressure zone on the upstream channel during the upstream propagation process. As shown in Fig. 5(a), the Case5 mainstream channel can be seen. The pressure difference between the left and right walls is the largest, and the lateral pressure gradient at the junction of the main channel and the dilator is also the largest in Fig. 5(b). On the other hand, when the amplitude of the microjet actuator is reduced, the vorticity of the vortex pair generated by the microjet is small (Fig. 6), and the vorticity of the microjet is difficult to break the free shear layer generated by the mainstream, thus controlling the mainstream. It is weakened. In summary, the larger the amplitude of the microjet actuator, the higher the control efficiency of the microjet to the mainstream.

| Working condition | Case5 | Case9 | Case10 |
|-------------------|-------|-------|--------|
| Deflection angle \( \phi \) (°) | 52.63 | 6.218 | 35.50 |

Table 2. Effect of different amplitudes of actuators on mainstream deflection.

![Figure 5(a). Comparison of left and right wall pressures of different amplitudes.](image1)

![Figure 5(b). Comparison of lateral pressure at different amplitude joints.](image2)

![Figure 6. Comparison of different amplitude microJet vortices.](image3)
4.4 Frequency impact on the mainstream

When the \( \gamma \) angle of the Case3, Case11, and Case12 simulating dilator is 30°, the effect of the microjet actuator on the mainstream control at different frequencies; When the \( \gamma \) angle of the Case6, Case13, and Case14 simulating dilator is 30°, the effect of the microjet actuator on the mainstream control at different frequencies. Table 3 shows the mainstream control efficiency of the microjets in different conditions of Case3, Case6, and Case11-Case14. It can be seen from Table 3 that when the \( \gamma \) angle of the divergence angle is 30°, the change of the frequency of the microjet actuator does not change significantly to the main control effect, which is consistent with the Pack and Seifert experiments; and when the \( \gamma \) angle is 60°, The control efficiency of the microjet to the mainstream is quite obvious.

As can be seen from Fig. 7, the frequency of the microjet actuator is increased, and the vorticity of the microjet is greatly increased near the main exit. However, when the AAA angle is 30°, the AAA angle is relatively small, and the vortex of the microjet does not have sufficient space to be fully developed, so that the vortex pair can only migrate downstream along the semi-expansion angle of the dilator. Therefore, the dilator limits the control of the microjet to the mainstream.

**Table 3.** Influence of microjets on the mainstream at different frequencies.

| Working condition | Case3 | Case11 | Case12 | Case6 | Case13 | Case14 |
|-------------------|-------|--------|--------|-------|--------|--------|
| Deflection angle  | \( \phi \) (°) | 40.77  | 40.53  | 40.80  | 35.12  | 34.27  | 41.14  |

**Figure 7.** Contour map of vorticity near the mainstream exit at different frequencies.

When the AAA angle reaches 60°, the wall effect of the microjet is not obvious when it is 50°. But the microjet vortex has plenty of room to develop. Therefore, as the frequency of the microJet actuator increases, the vortex vorticity increases. The increase of the microjet free shear layer significantly
enhances the traction of the mainstream. Therefore, the effect of the microjet on the main flow control is enhanced.

4.5 Effect of actuator position

Table 4 shows the effect of the microjet actuator on the main flow control at different positions of the dilator when the \( \gamma \) angle of the dilator is 70°. As can be seen from Table 4, when the microjet actuator is in the middle of the dilator, that is, the microjet actuator is at a distance of \( L\sin(\gamma)/2 = 6\sin(70°)/2 = 2.8\text{mm} \) from the main flow, the microJet has the best control efficiency to the main stream, and the actuator is located in other parts of the dilator. That is, the distance between the microjet and the mainstream \( c\sin(\gamma) = 1.6\sin(70°) = 1.5\text{mm or 5mm} \) is not as good as Case7. This is because the distance between the Case15 microjet and the mainstream is too small to establish a low-pressure recirculation zone, which causes the pressure difference between the left and right wall surfaces to affect the control efficiency. Case16 is due to the increase of the distance between the microjet and the main stream, and the effect of the microjet free shear layer on the main stream is reduced to reduce the efficiency of the microjet to the mainstream control. From the selected working conditions, the optimal distance of the microJet to the main control is 2.8mm (5.6h), not 3h without the dilator [4,5]. Therefore the dilator changes the optimal distance of the microjet to the mainstream control. At the same time, it can be seen from Table 4 that the main deflection angle does not change much, without the jet vector control of the dilator, the mainstream is very sensitive to d, and the mainstream is almost unaffected by the actuator when \( d>5h \) [4, 5 ], that is, the dilator reduces the sensitivity of the distance between the actuator and the main stream. In Fig. 8, when the semi-expansion angle is 70°, the velocity cloud map of the mainstream is controlled by microjet at

| Working condition | Case7 | Case15 | Case16 |
|-------------------|-------|--------|--------|
| Deflection angle  | \( \varphi \) (°) | 28.13  | 25.74  | 27.32  |

Table 4. Control effect of microjets at different positions on the mainstream at an angle of 70°.

In summary, the dilator increases the optimal distance of the microjet to the mainstream control; at the same time reduces the sensitivity of the microJet control efficiency to d, which reduces the placement accuracy of the microjet actuator in the flow field.

4.6 Effect of mainstream speed

Table 5 shows the control effect of the microjet on the mainstream under different mainstream speed conditions when the \( \gamma \) angle of the dilator is 70°. It can be seen from Table 5 that as the mainstream speed increases, the control efficiency of the microjet to the mainstream decreases. This is because when
the mainstream speed increases, the fluid absorbed by the actuator from the main flow to the cavity is relatively less in the "suction" process, and the free shear layer formed by the main stream is less likely to be broken, and the control efficiency of the microjet to the mainstream is reduce. Therefore, if the mainstream speed is too large, in order to obtain a better deflection effect, it is also necessary to increase the amplitude of the actuator to obtain a large exit speed. Figure 9 is a flow field velocity diagram of the mainstream of different speeds when the \( \gamma \) angle is 70\(^\circ\). Table 6 shows the effect of microjets on the control efficiency of the mainstream under different mainstream speeds when the \( \gamma \) angle is 40\(^\circ\). It can be seen from Table 6 that when the \( \gamma \) angle is 40\(^\circ\), the control effect of the microjet has changed significantly with the change of the mainstream speed, but the control effect of the microjet on the mainstream is better than that when the \( \gamma \) angle is 70\(^\circ\). The efficiency is high. Therefore, when the mainstream speed is increased, the dilator suitable for the semi-expansion angle can be used to control the main stream. Figure 10 is a flow field velocity diagram of the mainstream of different speeds when the \( \gamma \) angle is equal to 40\(^\circ\).

**Table 5.** Control effect of microjet on different speed mainstream when \( \gamma \) angle is 70\(^\circ\).

| Working condition | Case 7 | Case 17 | Case 18 |
|-------------------|--------|---------|---------|
| Deflection angle  |        |         |         |
| \( \phi (^\circ) \) | 28.13  | 15.58   | 9.64    |

**Table 6.** Control effect of microjet on different speed mainstream when \( \gamma \) angle is 40\(^\circ\).

| Working condition | Case 4 | Case 19 | Case 20 |
|-------------------|--------|---------|---------|
| Deflection angle  |        |         |         |
| \( \phi (^\circ) \) | 49.44  | 33.69   | 21.76   |

**Figure 9.** Flow field velocity map of different speeds at AAA angle of 70\(^\circ\).

**Figure 10.** Flow field velocity map of different speeds at AAA angle of 40\(^\circ\).
5. Conclusion
In this paper, the full-flow field calculation model X-L model of the microjet actuator is used to simulate the mainstream of the microjet directional control belt expander. The calculation results show:
1. The semi-expansion angle of the dilator has a significant effect on controlling the main stream. When the AAA angle is small (AAA < 50°), the wall-attached flow of the microjet plays a major role, which makes the mainstream almost along the wall of the dilator faces downstream; when the angle is large (AAA > 50°), the coupling of the microjet and the main shear layer plays a major role.
2. The dilator can reduce the sensitivity of the frequency to the microjet vector control effect, so that the microjet vector control reduces the requirement on the microjet frequency characteristics.
3. The dilator can reduce the sensitivity of the distance between the microjet actuator and the main stream to the microjet control effect, thereby reducing the precision of the arrangement of the microjet actuator in the flow field.
4. In the case of a large mainstream speed, a suitable expander can be selected to implement the most effective control of the

6. References
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