Numerical study on Vectoring the primary flows with dilator using microjet actuators

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Abstract. The synthetic flow field of Vectoring control of a primary flows with dilator using microjet actuators was Numerical studied by the overall flow field calculation model-X-L model. The result shows that the primary flows with dilator deflected larger than no one. And the angle of dilator has an optimal value. The reason of primary flows deflected was analyzed. There are three stage sections that the “low pressure closed reticular flow region” results in non-equilibrium of pressure along the primary jet’s orifice; the microjet roll sucked and the primary flow coupled in each other in the near catchment area; the microjet and the primary flow coupled in each other in the far catchment area.

1. Introduction
Micro-jet technology is a new type of active control technology for flow field [1]. The theoretical and experimental results at home and abroad show that micro-jet can indeed control the flow field [2]. The micro-jet actuator has the characteristics of miniaturization and zero net mass flow rate. The working fluid injected during operation is all derived from environmental fluid. The control system is simple, light and consumes very little electric energy. Its superiority is the traditional control method. (such as secondary injection) is unmatched. In addition, microfluidic technology can be used to enhance mixing, control heat transfer, reduce drag, and aerodynamic control and internal flow matching.

In view of the remarkable characteristics of micro-jets and the possibility of making breakthroughs in the active control technology of jets, many research institutes and universities at home and abroad are conducting extensive research on their mechanisms, experiments and applications [3~7], has achieved a series of results. In the experiment of Pack and Seifert [8], a dilator was attached to the outlet of the nozzle, and a microjet actuator was installed at the joint between the nozzle and the dilator. The actuator was arranged in the circumferential direction, and the mainstream outlet was fully developed. Turbulent flow. The change of the export structure makes the result of the interaction between the microjet and the mainstream different from the structure without the expander. This paper intends to analyze the situation numerically and explore its mechanism.

2. Control equations and numerical methods
Through the preliminary analysis of the synthetic flow field of the microjet and the main jet, a two-dimensional, incompressible Favre average N-S equation is proposed. Compared with the calculation accuracy and computational efficiency of the turbulence model, combined with the characteristics of the microjet flow field, the SST k-ω turbulence model is used in this paper. Comparing the characteristics of the simplified model of the microactuator, the X-L full flow field calculation domain model is used to verify the rationality of the model by comparing the numerical simulation results with the
experimental results under the same conditions of the Smith experiment [1].

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 x 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.

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

![Figure 2. Partial view of the grid at the main exit.](image2)

4. Calculation results and analysis

4.1 Calculation conditions
The calculation conditions of the microfluidic actuator for the main control of the belt expander are shown in Table 1. The mainstream speed is the velocity amplitude of the microjet vibrating film. Case 0 is the basic working condition when the semi-expansion angle of the dilator is 20° and the actuator is not working. Case 1 to Case 8 are numerical experiments in which the microfluidic actuator is controlled in the mainstream when the semi-expansion angle of the expander is different. When the microfluidic 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 $U_m = 5m/s$.

| Working condition | $\gamma$ (°) | $A_m$ (mm) | f (Hz) | $U_m$ (m/s) | d (mm) | $U_0$ (m/s) |
|-------------------|--------------|------------|--------|-------------|--------|-------------|
| Case 0            | 20           | 0          | 0      | 0           | 1.0261 | 5           |
| Case 1            | 10           | 2          | 400    | 5           | 0.5209 | 5           |
| Case 2            | 20           | 2          | 400    | 5           | 1.0261 | 5           |
| Case 3            | 30           | 2          | 400    | 5           | 1.5    | 5           |
4.2 Influence of different expansion angles on mainstream deflection

Figure 3 is a flow field velocity equivalence map of the microfluidic actuator for the main flow vector control of the dilator with different $\gamma$ angles at $t^* = 0$. Figure 3 shows that the main flow direction does not change when the microfluidic actuator is not operating; the main flow undergoes different degrees of deflection when the microfluidic actuator is operating. Under the condition that the mainstream speed and the microfluidic actuator parameters are consistent, the diversers of different $\gamma$ angles have different main vector deflection angles caused by the macroscopic mainstream of microfluidic control (ie, the control efficiency is different). Compared with the control efficiency of the micro-jet control in different gamma angles, when $\gamma < 50^\circ$ (Case1 to Case5), the mainstream control efficiency increases significantly with the increase of the semi-expansion angle; and when $\theta \geq 50^\circ$ (Case5 to Case8), With the further increase of the gamma angle, the control effect of the mainstream does not increase significantly, but decreases.

| Case | $\Delta$ | $\theta$ | $U_{main}$ | $\theta_{deflection}$ | $\Delta_{eff}$ |
|------|----------|----------|------------|---------------------|--------------|
| 4    | 40       | 2        | 400        | 5                   | 1.9284       |
| 5    | 50       | 2        | 400        | 5                   | 2.2981       |
| 6    | 60       | 2        | 400        | 5                   | 2.5981       |
| 7    | 70       | 2        | 400        | 5                   | 2.8191       |
| 8    | 80       | 2        | 400        | 5                   | 2.9544       |
Case 6

Case 7

Case 8

Figure 3. Flow field velocity contour map of mainstream vector control with different γ angle microfluidic actuators.

The downstream mainstream vector deflection angle $\phi$ is calculated by

$$\phi = \tan^{-1}\left(\frac{x_- + x_+}{2y}\right)$$

Among them, $x_-$ and $x_+$ are the $x$ coordinate values of the macro mainstream at the downstream $y$ corresponding to the velocity value $U = 0.5U_0$. Take $y = 2$ mm, the table below corresponds to the calculation results of $x_-$, $x_+$ and downstream vector deflection angles.

It can be seen from Table 2 that the γ angle has a significant influence on the main jet deflection of the micro-jet control, which is most obvious at $\gamma = 50^\circ$, and the main stream is deflected by 52.63°.

| Working condition | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 | Case 7 | Case 8 |
|-------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| $\gamma (^\circ)$ | 10     | 20     | 30     | 40     | 50     | 60     | 70     | 80     |
| $x-$              | -12.1  | -18.8  | -26.2  | -34.7  | -38.9  | -23.8  | -18.9  | -14.6  |
| $x+$              | 0.98   | -04.2  | -8.3   | -12.0  | -13.3  | -5.1   | -2.8   | -0.1   |
| Deflection angle  | 15.51  | 29.87  | 40.77  | 49.44  | 52.63  | 35.12  | 28.50  | 20.15  |

4.3 Analysis of control mechanism

The micro-jet actuator generates the working process and mechanism of the jet and the mainstream interaction. Taking Case6 as an example, the mechanism of the micro-jet to the mainstream is explained. The control of the microfluid to the main stream is divided into three stages: the micro-jet and the mainstream interaction propagate upstream in the low-pressure region between the two jets to cause the pressure gradient in the channel; the near-stream downstream of the jet outlet, and the entrainment and ejection of the jet to the mainstream; The far region downstream of the jet outlet, the coupling of the microjet and the mainstream.

4.3.1 within the mainstream channel

The microjet and the main flow are coupled to each other to form a low pressure region between the two jets, and the low pressure region propagates upstream to cause a pressure gradient in the main channel.

Figure 4 shows the corresponding pressure contour map ($p - p_0, p_0$ is the working environment pressure) near the exit of the main channel at different times of the microjet operation. The calculation results show that whether the actuator works in the "blowing" process or the "suction" process, there is a low pressure zone between the two jets under the mutual coupling of the microjet and the main stream.
In the low velocity flow field, the low pressure zone has the ability to diffuse to the periphery, which diffuses upstream, causing a pressure gradient to form within the main flow channel, thereby creating a pressure differential across the walls. Figure 5 corresponds to the pressure comparison of the two walls in the mainstream channel of Case 6 at different times in a cycle. PL is the pressure on the left wall and PR is the pressure on the right wall. When the actuator is working, the low pressure in the main channel is mainly concentrated in the region of \(-15\, \text{mm} < y < -3\, \text{mm}\).

Figure 4. Pressure contour map near the exit of the mainstream channel at different times in a cycle.
4.3.2 Nearstream of the jet outlet

In the near region downstream of the microfluidic outlet, the microfluid has a different effect on the main flow depending on the working state of the microfluidic actuator. When the microfluidic actuator works in the "blowing" process, the effect of the microjet on the main stream is mainly the traction of the free shear layer. As shown in Fig. 6(a), the mainstream deflects toward the microjet under the traction of the momentum momentum of the microfluid, and forms a flow saddle point P between the microjet and the main stream. The flow saddle point P corresponds to the main stream vector angle, and it will be mainstream. Divided into two parts, a part of the main stream is deflected toward the micro jet and merges with the micro jet, and the other part continues to flow downstream in its original direction. As shown in Fig. 6(b), when the microfluidic actuator operates in the "suction" process, a flow saddle point S is formed downstream of the actuator outlet, and the main flow continues to deflect toward the microjet side under the action of the microfluid entrainment. Part of the main flow that continues to deflect toward the microjet is divided into two parts by the flow saddle point S, one part is sucked into the actuator chamber by the microfluidic actuator, and the other part is not sucked into the actuator cavity, but is still sucked by the actuator Act and continue to deflect toward the side of the actuator.

4.3.3 The downstream area of the jet outlet

In the far region downstream of the microjet outlet, the microjet interacts with the mainstream free shear layer in the downstream migration and merges into the mainstream. As shown in the vortic contour map of the flow field in Fig. 7, it can be seen that the microjet is actuated. At different times of the working of the device, the vorticity on both sides of the main stream is always asymmetrical, and one side of the micro jet is stronger than that without the micro jet, so the main stream continues to deflect toward the side of the micro jet. In this area, the microjet has a significant flow-attachment effect, but this effect mainly acts on the micro-jet to work in the "blowing" process. As shown in Fig. 6(a), the flow direction
of the microfluid itself is obviously inclined to the left, and the micro-jet is deflected to the left to further deflect the main stream.

![Figure 7. Micro-jet vorticity contour map at different times.](image)

In summary, the main process of microfluidic control is that the physical process of vector deflection is divided into three different stages: in the first stage, in the mainstream channel, the lateral force formed by the main channel pressure gradient caused by the actuator work is biased toward the mainstream. The main vector is deflected at the exit; in the second stage, in the near-mainstream downstream of the main stream, the entrainment and ejector of the micro-jet to the main stream further deflects the main stream; the third stage, in the far-field downstream of the exit, the micro-jet Coupling with the mainstream free shear layer to further deflect the mainstream vector. Therefore, the mainstream final deflection angle is the sum of the microfluidic biasing effects that it experiences when undergoing three different stages.

The main stream vector control of the microjet is essentially that the macroscopic mainstream flow is controlled by the microjet in the above three stages. The pressure gradient caused by the microfluidic actuator work and the microfluidic actuator work on the "sucking" process to the mainstream volume. Suction and working in the "blowing" process micro-fluid flow impulse to the mainstream of the ejection effect, and the micro-jet in the downstream migration process and the mainstream free shear layer mutual coupling effect is the micro-jet actuator for the macro low-speed mainstream The main mechanism of vector control.

5. Conclusion
In this paper, the full-flow field calculation model X-L model of the micro-jet actuator is used to simulate the mainstream of the micro-jet directional control belt expander. The calculation results show:

- Under the action of microjet, the mainstream deflection of the belt expander is greater than that of the main stream without the expander, and there is an optimal expansion half angle. When the extended half angle $\gamma=50^\circ$, the mainstream deflection is the largest. Up to 52.63 $^\circ$.
- Analyzed the biasing mechanism of microjet to the mainstream. The physical process of microfluidic control of mainstream deflection is divided into three different stages: the first phase, in the mainstream channel, the main channel pressure gradient caused by the actuator work. The lateral force is biased to the mainstream, and the mainstream vector is deflected at the exit. In the second stage,
in the near-streaming zone of the mainstream outlet, the micro-jet is mainly deflected by the entrainment and ejector of the main stream; the third stage is in the far downstream zone of the outlet, the microjet and the mainstream free shear layer are coupled to each other to further deflect the mainstream vector. Therefore, the mainstream final deflection angle is the sum of the microfluid biasing effects that it experiences when undergoing three different stages.

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