**Numerical Study on Vectoring Primary Flow with Adjacent Synthetic Jet with Dip Angle**

**Feng Gao, Qian Zhang**, Fengli Chen, Chengtao Zhang, Xuefeng Xia

Air and Missile Defense College, Air Force Engineering University, Shaanxi Xian 710051, China

*Corresponding author’s e-mail: zhangqian8913@163.com*

**Abstract.** Based on the full flow field calculation model of the synthetic jet actuator-X-L model, numerical simulation is carried out on the influence of the main parameters of the directional control of the adjacent synthetic jet actuator, and the parameters of the actuators of different adjacent synthetic jets are analyzed. The amplitude, frequency, and phase difference of the device were analyzed. The results show that the larger the amplitude of the synthetic jet actuator, the more obvious the control effect of the synthetic jet on the main stream; the synthetic jet actuator has an optimal frequency, so that the main stream deflection efficiency is the highest, and the inclination angle lowers the optimal frequency, which reduces the requirement of the flow field control on the actuator frequency; the actuator phase difference makes the control efficiency adjustment width of the mainstream increase significantly, and there is an optimal phase difference, while right Side actuator phase advancement is more efficient than hysteresis control.

1. **Introduction**

Synthetic jet actuators are the most active active flow control technology in the field of flow control for more than a decade [1]. A number of foreign scientific research institutions and universities are conducting research on mechanisms, experiments and applications [2–6]. In the domestic defense science and technology university, Northwestern Polytechnical University, Beijing University of Aeronautics and Astronautics, etc. in the actuator calculation model [7], adjacent actuator interaction mechanism [8], actuator influence factors [7, 9], synthetic jet Some results have been achieved in velocity characteristics [10], synthetic jet actuator enhanced gas/oxygen blending [11], and synthetic jet actuator low speed vector control [12–15, 16–18]. At present, the application of synthetic jet actuators for jet vector control has been paid attention to. It is based on the theory that small-scale disturbances cause large macroscopic effects and opens up a new way for vector control, making vector control technology possible to achieve breakthroughs.

Although the synthetic jet can produce a certain vector deflection for a low speed mainstream under given parameters, the energy of the synthetic jet actuator is limited and the deflection angle is also limited. If the synthetic jet actuator exit axis is deflected and the exit velocity is ejected at a certain angle, this does not increase the input power of the actuator, nor does it change the magnitude of the actuator exit velocity, but the vortex structure near the exit of the device was changed, so that the control efficiency of the synthetic jet to the mainstream can be changed. In order to reveal the influence of synthetic jet actuators on the control efficiency of the mainstream under different working conditions, and to optimize the control of the mainstream, this paper introduces the mainstream control and parameter analysis of adjacent synthetic jets with dip angle under different conditions.

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2. Numerical analysis method

2.1. Control equations and numerical methods

The flow velocity of the main flow and the actuator outlet in the flow field calculated in this paper is not high, so it can be assumed that the flow field is incompressible and only two-dimensional processing is carried out, while considering the viscous and unsteady characteristics of the flow, solving two-dimensional and non-linear The constant and incompressible Reynolds time-averaged N-S equation. The governing equation is as follows:

\[
\begin{align*}
\Delta \cdot \mathbf{u} & = 0 \\
\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \Delta \mathbf{u} = -\nabla p + \left( \mu_1 + \mu_2 \right) \Delta^2 \mathbf{u}
\end{align*}
\]  

(1)

In the formula, \( \mu_1 \) and \( \mu_2 \) are laminar and turbulent viscosity coefficients, respectively. The second-order upwind interpolation format is used to spatially discretize the equation, while the time dispersion is in the first-order implicit format. The discrete solver is used to iteratively solve the discrete equation.

2.2. Calculation model and initial boundary conditions

The calculation model is numerically simulated using the actuator simplified model X-L. The mathematical expression of the actuator diaphragm is:

\[
u(t, l) = -2\pi \phi \left( 1 - \frac{l^2}{r^2} \right) \sin \left( 2\pi ft + \phi_0 \right)
\]

(2)

The flow field area and calculation grid near the macro mainstream exit are shown in Figure 1 and Figure 2. The main channel is 12 mm × 50 mm, the grid is 30 × 80, the actuator throat is 0.5 mm × 1 mm, and the grid is 10 × 30. The actuator cavity is 1.5 mm × 2.5 mm, the grid is 25 × 30; the outer flow field is 300 mm × 300 mm, and the grid is 300 × 200.

SJ_L and SJ_R are the boundary of the vibrating membrane of the actuator. According to the X-L model, the main inlet is set as the speed inlet condition, the two sides and the top surface of the outer flow field are free boundaries, and the other is the non-slip solid wall boundary.

The iterative calculation accuracy is that the sum of the normalized errors of all variables is less than 1×10^{-4}, the time step is T/100, and the maximum number of iterations is 50 times per time step. The simulation time is 0.2 s to ensure that the flow field is macroscopically stable.

3. Calculation results analysis

The calculation conditions for the main flow control with the angled synthetic jet actuator are shown in Table 1. The mainstream speed is \( U_o = 8 \) m/s and the synthetic jet velocity amplitude is \( U_m = 2\pi f A_m \).

The synthetic jet actuator frequency is \( f = 400 \) Hz, and the midpoint amplitude of the actuator film

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Figure 1. Computational domain and grid

Figure 2. Computational domain and grid computing domain and grid
is $A_m=2$ mm, so that the maximum velocity of the midpoint of the actuator film is $U_m=5$ m/s.

Table 1. Synthetic flow actuator mainstream vector control working conditions

| Working condition | $\theta$ (°) | $A_m$ (mm) | $U_m$ (m/s) | $f$ (Hz) | $\Delta\phi$ |
|-------------------|--------------|------------|-------------|---------|------------|
| Case0             | 30           | 2          | 5           | 400     | 0          |
| Case1             | 50           | 0.4        | 1           | 400     | 0          |
| Case2             | 50           | 1.2        | 3           | 400     | 0          |
| Case3             | 30           | 4          | 5           | 200     | 0          |
| Case4             | 30           | 1          | 5           | 800     | 0          |
| Case5             | 30           | 2          | 5           | 400     | 30         |
| Case6             | 30           | 2          | 5           | 400     | 60         |
| Case7             | 30           | 2          | 5           | 400     | 90         |
| Case8             | 30           | 2          | 5           | 400     | 120        |
| Case9             | 30           | 2          | 5           | 400     | 150        |
| Case10            | 30           | 2          | 5           | 400     | 180        |
| Case11            | 30           | 2          | 5           | 400     | -30        |
| Case12            | 30           | 2          | 5           | 400     | -60        |
| Case13            | 30           | 2          | 5           | 400     | -90        |
| Case14            | 30           | 2          | 5           | 400     | -120       |
| Case15            | 30           | 2          | 5           | 400     | -150       |

3.1. Influence of actuator amplitude $U_m$ on the mainstream

Table 2 shows the effect of actuator amplitude on the mainstream deflection effect at different amplitudes. It can be seen from Table 2 that the greater the velocity amplitude, the higher the control efficiency of the synthetic jet to the mainstream. On the one hand, the larger the velocity amplitude of the synthetic jet actuator, the more fluid is taken between the synthetic jet and the mainstream in the "crushing" process due to the shearing force; the more fluid is sucked in the "suction" process. Therefore, the stronger the low-pressure zone formed between the synthetic jet and the mainstream, the greater the influence of the low-pressure zone on the upstream channel during the upstream propagation process. As shown in Fig. 3, the pressure difference between the left and right wall faces near the exit of the mainstream channel of Case0 is the largest (In Fig. 3, L represents the left wall surface and R represents the right wall surface. Figure 4 shows that the lateral pressure gradient at the exit of the mainstream channel of Case0 is also the largest.) On the other hand, when the amplitude of the synthetic jet actuator is reduced, the vorticity of the vortex pair produced by the synthetic jet is small (Fig.5), and the vorticity of the synthetic jet is insufficient to break the free shear layer produced by the mainstream, Case1 and Case2 the vortex formed is basically engulfed by the mainstream, and the ability to control the mainstream is very limited. In summary, the greater the amplitude of the synthetic jet actuator, the higher the control efficiency of the synthetic jet to the mainstream.

Table 2. Effect of actuator amplitude on mainstream deflection at different amplitudes

| Working condition | Case0 | Case1 | Case2 |
|-------------------|-------|-------|-------|
| Deflection angle $\phi$ (°) | 23.84 | 1.90  | 4.35  |
3.2. The impact of frequency $f$ on the mainstream

Table 3 shows the effect of the synthetic jet actuator on mainstream control at different frequencies. It can be seen from Table 3 that when $\theta$ is 30°, $f$ is optimal in $f = 400$ Hz in several operating conditions taken. On the one hand, the frequency is too low, the “blow” and “suction” strokes become longer in one cycle, and the vortex generated by the jet is more easily dissipated. As shown in Figure 6, the vorticity of Case3 is smaller than that of Case4 and Case0, thus reducing the mainstream control efficiency. On the other hand, the frequency is too high, the synthetic jet period is short, and the low pressure region between the jet and the mainstream is relatively reduced. As shown in the comparison between the wall pressure of Fig. 7 and the lateral pressure at the main exit of Fig. 8, Case4 is obviously smaller than Case0 and Case3. Therefore, $f$ has an optimum value that maximizes the mainstream deflection angle.

| Working condition | Case0 | Case3 | Case4 |
|-------------------|-------|-------|-------|
| Deflection angle $\phi$ (°) | 23.84 | 10.14 | 11.41 |
3.3. Influence of phase difference $\Delta \Phi$ on mainstream control effect

Fig. 9 is a contour diagram of the flow field velocity at different phase differences $\Delta \Phi$ when the $\theta$ angle is 30°, reflecting the influence of the adjacent synthetic jet actuators on the main vector control effects under different phase differences. Numerical simulations show that the phase difference plays an important role in the control of adjacent synthetic jet vectors. Table 4 gives the angles of the mainstream deflection for different phase differences. As can be clearly seen from Fig. 9 and Table 4, firstly, the phase difference $\Delta \Phi$ has a large adjustment width for the main stream vector control, from 7.98° to 38.76°, and the adjustment width is 30.87°. Secondly, the phase difference $\Delta \Phi$ has an optimum value $\Delta \Phi_m$. When $0 < \Delta \Phi < \Delta \Phi_m$, the vector deflection angle of the main stream increases as $\Delta \Phi$ increases. When $\Delta \Phi > \Delta \Phi_m$, the deflection angle of the main stream does not increase as $\Delta \Phi$ further increases. Instead, in the case selected in this paper, $\Delta \Phi_m = 60$, the mainstream vector is deflected by 38.76 °.

It can be seen from Fig. 10 and Fig. 9 that, due to the fact that the vortex is biased to the left in the working condition Case5, the distance between the vortex pair and the main flow is increased, and the degree of coupling between the vortex pair and the main stream is small; The Case6 vortex has a large intensity, the distance between the vortex pair and the main stream is small, and the vortex pair has the largest coupling degree with the mainstream. Therefore, the control efficiency to the mainstream is the highest at $\Delta \Phi = 60°$. As $\Delta \Phi$ continues to increase, the vorticity of the vortex pair decreases (see Figure 10), so the control efficiency of the synthetic jet to the main stream is also reduced. When $\Delta \Phi < 0$, that is, when the right actuator phase lags, the fusion cancellation effect of the vortex pair is weakened, and...
the vortex pair separation (Fig. 10) is controlled by two independent vortex pairs, while the left vortex is opposite to the mainstream. Far, the control efficiency is limited. As $\Delta \Phi$ increases, the separation effect becomes more obvious, so the control efficiency to the mainstream is also lower.

Table 4. Control effect of the mainstream of synthetic jets with different phase differences at $\theta=30^\circ$

| Working condition | Deflection angle | Working condition | Deflection angle | Working condition | Deflection angle | Working condition | Deflection angle |
|-------------------|-----------------|------------------|-----------------|------------------|-----------------|------------------|-----------------|
| Case5             | 27.56           | Case18           | 28.69           | Case3            | 23.84           | Case23           | 18.78           |
| Case6             | 38.76           | Case19           | 23.49           | Case21           | 20.72           | Case24           | 10.82           |
| Case7             | 30.33           | Case20           | 17.52           | Case22           | 19.19           | Case25           | 7.98            |

Case5  
Case6  
Case7  
Case8  
Case9  
Case10  
Case0  
Case11 
Case12
Figure 9. Contour map of synthetic jet velocity at different phase differences.
4. Conclusion
In this paper, the numerical simulation of the jet flow vector control of the synthetic jet with dip is carried out. The effects of different adjacent synthetic jet actuator parameters (actuator amplitude, frequency, phase difference), synthetic jet incident angle and the relative position of the synthetic jet and the main stream on the mainstream control efficiency are analyzed. Obtain the following conclusions:

(1) The larger the amplitude of the synthetic jet actuator, the more obvious the control effect of the synthetic jet on the main stream. On the one hand, the larger the velocity amplitude of the synthetic jet actuator, the stronger the low pressure region formed between the synthetic jet and the main stream, and the greater the influence on the mainstream; on the other hand, when the synthetic jet actuator amplitude is reduced, the synthesis vortex generated by the jet has a small vorticity and limited control over the mainstream.

(2) The existence of the optimal frequency makes the mainstream deflection efficiency the highest. On the one hand, the frequency is too low, the "blow" and "suction" strokes become longer in one cycle, and the vortex generated by the jet is more easily dissipated; on the other hand, the frequency is too high, the synthetic jet period is short, and the low pressure region between the jet and the main stream is relatively Reduced.

(3) The phase difference causes the main control efficiency adjustment width to increase significantly, and there is an optimum phase difference, while the right actuator phase advance is higher than the hysteresis control efficiency.

References
[1] McMichael J M. Progress Prospects for active Flow Control Using Microfabricated Electro-Mechanical System(MEMS), AIAA 96-0306.
[2] Glezer. A, Amitay M. Synthetic jets[J]. Ann Rev Fluid Mech,2002,34,503-529.
[3] Luo Zhenbing, Xia Zhixun. Synthetic Jet Technology and Its Application in Flow Control[J].Advances in Mechanics,2005,35(2):221-234.
[4] Lee C, Hong G, A piezoelectrically actuated micro synthetic jet for active flow control [J]. Sensors and Actuators A, 2003,108(1),168-174.
[5] Wang H, Menon S. Ruel-air mixing enhancement by Synthetic micro-jets [J].AIAA J,2001,39(12):2308-2319.
[6] Zhao Hong, Yang Zhiguo, Pei Huijuan. Experimental study on flow characteristics of synthetic jets and its application in combustion[J].Journal of Aerospace Power,2004,19(4):512-519.
[7] Mittal R, Rampunggoon P. On the virtual aero-shaping effect of synthetic jets [J]. Physics of Fluid, 2002,14 (4): 1533-1536.
[8] LUO Zhen-bing, XIA Zhi-xun. A novel valve-less synthetic jet based micro-pump [J]. Sensors Actuators A,2005,122(1):131-140.
[9] Ding Henggao. Micro/Nano Technology——Two-Phase Technology for the 21st Century[J]. Chinese Journal of Scientific Instrument, 1995,16(1):1-4.
[10] Lang W. Reflexions on the future of Microsystems[J]. Sensors and Actuators A, 1999, 72: 1-15.
[11] Wang Liding, Liu Chong. Development trend of MEMS science and technology[J]. Journal of Dalian University of Technology, 2000, 40(5): 505-508.
[12] Shao Peige, Wang Liding. Progress in Micromechanical Components and New Instruments[J]. Optical Precision Engineering, 1999, 7(1): 10-15.
[13] Cui Erjie. MEMS and Intelligent Fluid Dynamics[J]. Journal of Aerodynamics, 2000, 18(Supplement): 52-58.
[14] Kral L D, Active Flow Control Technology, ASME Fluids Engineering Division Technical Brief.
[15] Smith B L, Glezer A. The formation and evolution of synthetic jets[J]. Physics of Fluids, 1998, 10(9): 2281-2297.
[16] Gao Feng, Wang Liang, Mainstream numerical simulation of single microfluid actuator orientation control, Journal of Northwestern Polytechnical University, 2003, 21(5): 528-531.
[17] Gao Feng, Wang Liang, Zhang Zhifeng. Analysis of Main Parameters of Directional Control of Single Micro Jet Actuator[J]. Journal of Air Force Engineering University, 2003, 4(2): 12-15.
[18] Gao Feng, Wang Liang. Numerical Numerical Simulation of Directional Control of Double Micro Jet Actuators[J]. Journal of Aerodynamics, 2006, 24(3).
[19] Luo Zhenbing, Synthetic Jet/Synthetic Double Jet Excitation and Its Application in Jet Vector Control and Micropump [D] Changsha: National University of Defense Technology (PhD thesis) 2006.
[20] Glezer A, Amitay M. Synthetic jets[J]. Ann Rev Fluid Mech, 2002, 34, 503-529.