

# Effects of synthetic jet frequency on the separated flow in a diffusing S-duct

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**Abstract:** Numerical simulations were carried out to investigate the effects of synthetic jet actuation frequency on the separated flow in a diffusing S-duct. The Reynolds number based on the entrance height was  $9.78 \times 10^5$ . At first, the numerical model was validated with experimental data, and then, the interaction between the separated flow and the synthetic jets at different frequencies was discussed. The results demonstrate that the control effect is significantly dependent on the momentum mixing enhancement between inside of the separated boundary layer and the outer flow. There exists a narrow range of actuation frequency, in which effective separation control can be achieved using synthetic jets. A dimensionless frequency  $F^+ = 1.0$  is identified as the optimal frequency, with a momentum coefficient of  $1.62 \times 10^{-3}$ , the separation area is reduced about 46%, and the aerodynamic performance of the S-duct is also greatly improved compared to uncontrolled case. Further analysis reveals that the choice of actuation frequency is mainly determined by the momentum flux produced by a single ejection and the spacing between adjacent ejections, the optimal frequency case can be understood as a balance between the two factors. In addition, it is found that the synthetic jets can also suppress the secondary flows while decreasing the separation.

**Key words:** active flow control; boundary layer separation; synthetic jet; actuation frequency; S-duct

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S-duct inlets are widely used in military aircraft where design constraints require the engine to be buried into the fuselage. In addition to reducing radar cross section and infrared signatures, S-duct inlets are also beneficial to reduce the propulsion system size due to their compact geometries<sup>[1-2]</sup>. However, the flow in an S-duct is usually under strong streamwise adverse pressure gradient which can result in boundary layer separation. Furthermore, when the flow passes through the bends of S-duct, the centrifugal forces will establish lateral pressure gradients and induce undesired secondary flows. The combined effects of these flow structures can lead to a large amount of total pressure loss as well as flow distortion at the outlet of S-duct. Poor pressure recovery results in reduced overall engine performance and decreased fuel efficiency,

while distortion causes instabilities in the compressor dynamics and may even lead to compressor stall<sup>[3-4]</sup>. Therefore, The S-duct inlets require flow control techniques to minimize the pressure loss and distortion.

In recent years, synthetic jets have received a great amount of attention as a new type of active flow control technology. They have the ability to generate a plurality of vortices and to enhance the momentum transfer between the separated boundary layer and the outer flow, thus decreasing the separation<sup>[5]</sup>. The main advantage of synthetic jet actuators compare to steady blowing or suction devices is that they require one or two orders of magnitude less momentum to achieve the same performance improvement<sup>[6-7]</sup>. Moreover, synthetic jet actuators need neither the external fluid supply nor

the complex plumbing system. Amitay et al.<sup>[8]</sup> first used the synthetic jet as a flow control method to control the boundary layer separation over a circular cylinder, the results showed that the separation point moved downstream. Various studies have been performed on separation control of a two dimensional hump by the use of synthetic jets<sup>[9-11]</sup>, Avdis et al.<sup>[9]</sup> stated that the time-averaged separation length could be reduced by 30% at an proper actuation frequency. WANG et al.<sup>[12]</sup> designed a dual-slots synthetic jet actuator to control the separated flow over a NACA0015 airfoil at a freestream velocity of 27.3 m/s, they observed that when the actuator was operated at 160 Hz, the stall angle was increased by 4°. XIE et al.<sup>[13]</sup> also reported promising results using synthetic jets to delay the flow separation of a turbine blade.

However, most studies of synthetic jet-based separation control have only focused on external flows (such as the flow over an airfoil mentioned above), which are generally treated as two dimensional flows, little research has been conducted on the flow in an S-duct. Due to the presence of side walls, the S-duct flow field is highly three dimensional, the flow characteristics in the spanwise direction are not negligible. Meanwhile, the secondary flows provide an additional complication to the S-duct flow field and largely enhance the flow distortion at the outlet. Therefore, it is necessary to verify whether the synthetic jets could suppress the secondary flows while decreasing the separation. LI et al.<sup>[14]</sup> employed a synthetic jet array to delay separation in a diffusing S-duct, their study was successful in achieving its goal, but did not consider the three dimensional characteristics of the S-duct flow and the secondary flow suppression.

In addition, it is worth noting that among the actuation parameters of the synthetic jet like ejection velocity, actuation frequency, ejection angle, etc., actuation frequency is one of the most critical parameters, it strongly affects the efficiency of flow control, if not properly cho-

sen, actuation could have no effect or even negative effects<sup>[15]</sup>. Gissen et al.<sup>[16]</sup> and CHEN et al.<sup>[17]</sup> performed experimental and numerical studies, respectively, on the S-duct flow distortion reduction using synthetic jets, but these studies have not taken into account the effect of frequency.

The aim of this paper is to investigate the effects of synthetic jet frequency on the separated flow in a diffusing S-duct. Firstly, the numerical model was validated by comparing its predictions with experimental data. Then, the interaction between the separated flow and the synthetic jets was discussed in detail, the variation of separation region on the entire lower surface was examined. Furthermore, an optimal dimensionless frequency was identified with respected to the improvement of S-duct performance, and the suppression of secondary flow was also presented. The results of this study will be useful in developing effective separation control strategies based on synthetic jets.

## 1 Numerical modeling

Figure 1 shows the geometry of the S-duct, it starts with a square cross-section of side  $D$  ( $D=100\text{ mm}$ ) and ends with a rectangular cross-section of  $1.0D$  wide by  $1.6D$  high. The diffuser offset is  $1.4D$ , length is  $4.5D$ , and each end of the diffuser has a  $1.0D$  straight section, so the total length of the S-duct is  $6.5D$ . The center-line distribution and the area distribution of the diffuser were obtained from reference [18]. The coordinate system is the following:  $x$  is parallel with the incoming freestream,  $y$  is vertical, and

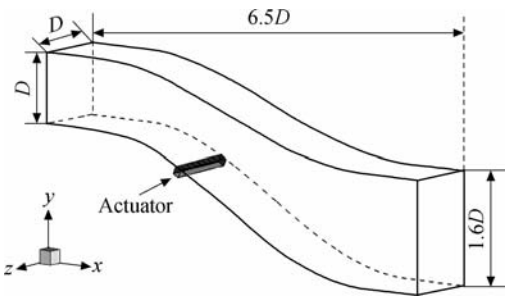


Fig. 1 Geometry of the S-duct with the synthetic jet actuator

$z$  is spanwise, the origin is located at the center of the diffuser entrance.

The synthetic jet actuator was placed on the lower surface of the S-duct, its orifices consist of eight rectangular slots of width  $d=0.005D$  and length  $l=20d$ . The layout of the slots is displayed in Fig. 2, the slots were oriented in streamwise direction and their leeward edges were located at the separation point of the uncontrolled flow.

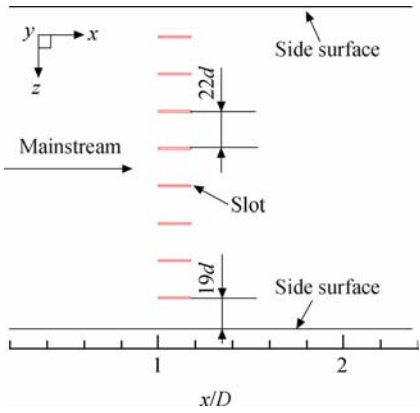


Fig. 2 Layout of the slots ( $x$ - $z$  view)

As shown in Fig. 3, all the slots were communicated with a single cavity, of which the bottom surface can performs piston-like motion to generate the synthetic jets. The cavity has a length of  $200d$  and width of  $20d$ .

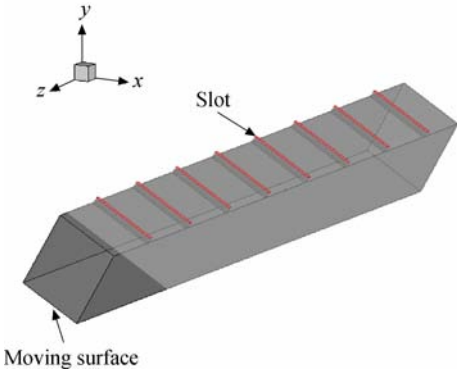


Fig. 3 Configuration of the synthetic jet actuator

Figure 4 displays the computational domain and mesh. The entrance of the duct was connected with a  $6.0D$  straight section, which is used to generate the incoming boundary layer to match the experimental conditions. Because the

geometry and boundary conditions are symmetrical about the  $x$ - $y$  plane, only a half model was constructed. The mesh was structured comprising of hexahedral elements of gradually increasing size from the surfaces to the center of the duct with a near wall spacing  $y^+ < 1$ . After conducting a grid independence study, a mesh of approximately 4.6 million nodes was chosen.

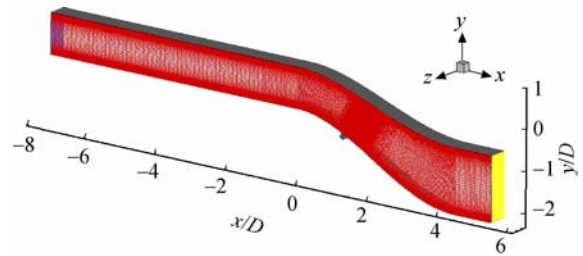


Fig. 4 Computational domain and mesh

A pressure inlet boundary condition was imposed at the entrance of the computational domain, the Mach number  $Ma_\infty$  at the S-duct entrance is equal to 0.42, corresponds to a Reynolds number of  $9.78 \times 10^5$ . The outlet plane is a pressure outlet boundary condition of which the static pressure is equal to the standard atmospheric pressure, no slip wall boundary conditions were used for all solid surfaces. For the uncontrolled case, the slots were set as no slip wall boundary conditions; while for the controlled case, sinusoidal variation was implemented on the whole cavity bottom surface to simulate piston-like motion by using dynamic mesh method<sup>[19]</sup>, the motion is given by

$$U(t) = U_{\text{act}} \sin 2\pi ft \tag{1}$$

where  $U_{\text{act}}$  is the maximum velocity of the cavity bottom surface, its value is related to the synthetic jets velocity,  $f$  is the frequency. The dimensionless frequency is defined by

$$F^+ = \frac{fL_u}{U_\infty} \tag{2}$$

where  $L_u$  is the separation length of uncontrolled flow,  $U_\infty$  is the freestream velocity. The time-averaged velocity of the jets over the ejection cycle is given by

$$\bar{V}_j = \frac{2}{T} \int_0^{T/2} V_o(t) dt \tag{3}$$

where  $T$  is the actuation period,  $V_0(t)$  is the synthetic jets velocity at the slots, the jets inject in a direction perpendicular to the lower surface of the duct. Five frequencies have been considered:  $F^+ = 0.2, 0.5, 1.0, 1.5$  and  $2.0$  (correspond to 88, 220, 440, 660 Hz and 880 Hz, respectively). The jet-to-freestream velocity ratio is defined by  $R = \bar{V}_j/U_\infty$ , which is fixed at 0.637, allowed the jets to penetrate the mainstream deep enough and ensure large momentum transfer<sup>[20]</sup>. Likewise, the momentum coefficient is defined by

$$C_\mu = 8 \frac{\rho_j \bar{V}_j^2 l d}{\rho_\infty U_\infty^2 D^2} \tag{4}$$

$C_\mu$  represents the ratio of momentum ejected by all the actuating synthetic jets to the characteristic momentum of the freestream, it equal to  $1.62 \times 10^{-3}$ . From the above equations, it is clear that the actuator amplitude varies with the actuation frequency for a fixed momentum coefficient, the higher the frequency, the smaller the amplitude.

The simulations were performed using the commercial computational fluid dynamics (CFD) code Fluent, a density-based solver was applied with an implicit scheme. In order to close the Reynolds-averaged Navier-Stokes (RANS) equations, we employed the shear stress transport (SST)  $k-\omega$  turbulence model which has a good performance for the flow separation and secondary flow<sup>[21-22]</sup>. A steady solver was used for the uncontrolled case, while a transient solver was implemented for the controlled case with each actuation period consisting of 200 time steps.

2 Validation of numerical model

An experimental study has been undertaken to validate the numerical model. The experiment was conducted in the transonic wind tunnel at the Thermal Energy and Power Engineering Institute of Beijing University of Aeronautics and Astronautics. As shown in Fig. 5, a straight section was installed at the exit of the wind tunnel, followed by an S-duct test section. Experimental data were obtained for the uncontrolled

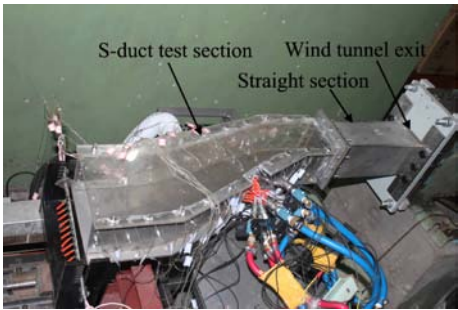


Fig. 5 S-duct test section

case with a Mach number of 0.42. Figure 6 presents the comparison of experimental and computed pressure coefficient  $C_p$  along the lower surface centerline. The pressure coefficient  $C_p = (p - p_\infty)/q_\infty$ , where  $p$  is the local static pressure,  $p_\infty$  and  $q_\infty$  are the duct entrance static pressure and dynamic pressure, respectively. The computed results agree well with the experimental data, the lower surface shows a pressure plateau between the two bends of the S-duct. This pressure plateau indicates that the boundary layer is properly separated in this region, more discussion will be given in the next section.

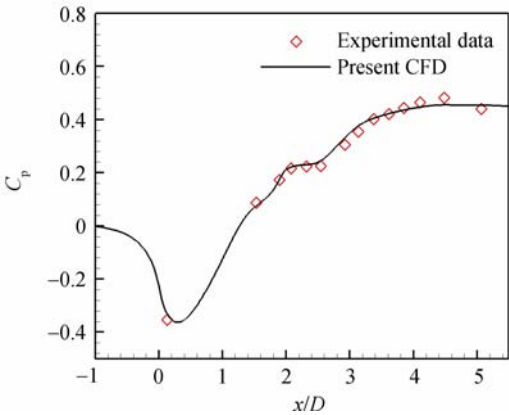


Fig. 6 Comparison of experimental and computed pressure coefficient  $C_p$  along the lower surface centerline

3 Results and discussion

The momentum mixing enhancement can be evaluated by the turbulence kinetic energy (TKE)<sup>[23]</sup>, which is the mean kinetic energy associated with the eddy structures. The TKE is given as

$$k = \frac{1}{2} (u'^2_{rms} + v'^2_{rms} + w'^2_{rms}) \tag{5}$$

where  $u'_{\text{rms}}$ ,  $v'_{\text{rms}}$  and  $w'_{\text{rms}}$  denote the root mean square velocity fluctuations in  $x$ -,  $y$ - and  $z$ -direction, respectively.

Figure 7 shows the close-up view of normalized TKE  $k/k_{\text{in}}$  in a  $y$ - $z$  plane (at  $\Delta x=20d$ ) during a synthetic jet actuation cycle for  $F^+=0.2$ , 0.5, 1.0, 1.5 and 2.0, respectively,  $k$  is the phase-averaged TKE,  $k_{\text{in}}$  is the averaged TKE at the S-duct entrance,  $\Delta x$  is the  $x$ -direction distance from the leeward edges of the slots. As can be observed, several high TKE regions are occurring near the lower surface because of the interaction between the actuating synthetic jets and the boundary layer. For  $F^+=0.2$  (Fig. 7 (a)),  $k/k_{\text{in}}$  reaches a peak at  $t/T=0.25$ , then rapidly decreases at  $t/T=0.5$ , and remains small in the rest phases,  $k/k_{\text{in}}$  exhibits strong fluctuations. For  $F^+=2.0$  (Fig. 7 (e)), the fluctuations are much weaker, but the value of  $k/k_{\text{in}}$  is not high enough, which indicates that the momentum transfer is insufficient. Nevertheless, the other three cases show more favorable results, particularly for  $F^+=1.0$  (Fig. 7 (c)), which exhibits notable high TKE regions until  $t/T=0.625$ , consequently, the momentum mixing enhancement in the separation region is substantial throughout the whole cycle.

The contours of normalized  $x$ -velocity  $u/U_{\infty}$  in a  $x$ - $y$  plane (at  $\Delta z=0.1725D$ ) during an actuation cycle for  $F^+=1.0$ , 0.2 and 2.0 are displayed in Fig. 8, Fig. 9 and Fig. 10, respectively,  $\Delta z$  is the  $z$ -direction distance from the S-duct symmetry plane. Four phases have been considered,  $\varphi=\pi/2$  and  $\varphi=3\pi/2$  are corresponding to the middle of the ejection cycle and the middle of the suction cycle, respectively. For  $F^+=1.0$ , as the vortical structures generated by the synthetic jets penetrate the boundary layer in the ejection cycle, a bulging structure is observed on the contour (Fig. 8 (a)). Then, the bulge moves downstream, entraining high momentum fluid into the separated region, thus decreasing the separation. This process can be seen in Fig. 8(b)—Fig. 8(d), the dashed lines show the transmission path of the bulges, just before its

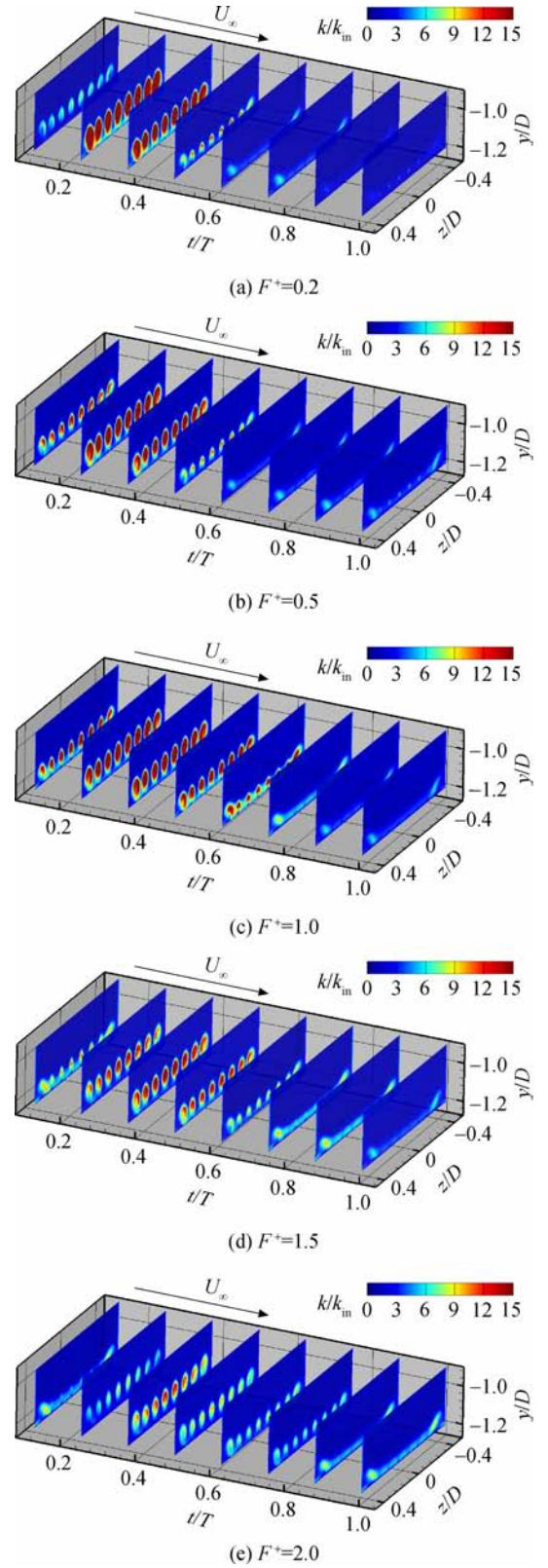


Fig. 7 Contours of normalized TKE  $k/k_{\text{in}}$  in a  $y$ - $z$  plane during an actuation cycle (close-up view near the lower surface at  $\Delta x=20d$ )

arrival, the local separated flow is forced downstream, when the bulge reaches the core of the separation region, a new bulge of the next cycle

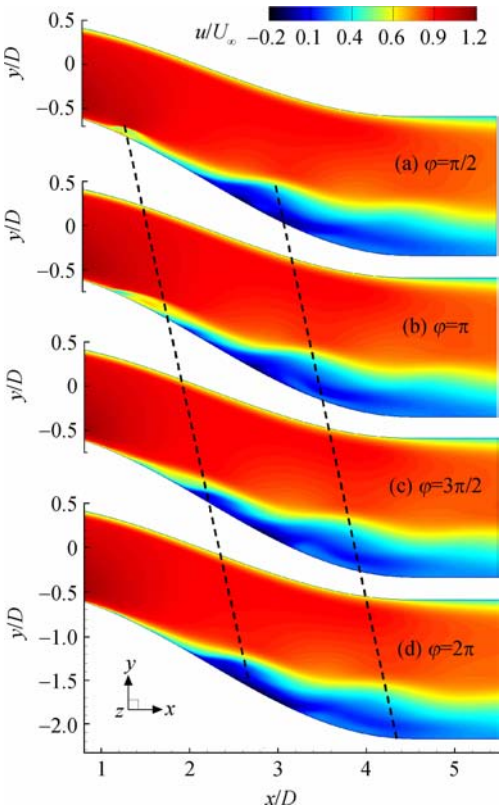


Fig. 8 Contours of normalized  $x$ -velocity  $u/U_\infty$  in a  $x$ - $y$  plane during an actuation cycle (at  $\Delta z=0.1725D$ ,  $F^+=1.0$ )

is exactly formed at the slot. Hence, the flow control remains effective in the entire actuation period and the size of the time-averaged separation region is reduced.

Furthermore, by comparing the contours of diffident phases, the bulge translational velocity  $U_b$  has been evaluated and it is equal to  $0.55U_\infty$ . Then, refer to the definition of  $F^+$ , a new dimensionless number can be given as

$$N = \frac{L_u}{U_b T} = \frac{f L_u}{U_b} \tag{6}$$

where  $N$  denotes the instantaneous number of bulges in the separation region, it depends on the interaction amongthe mainstream, separated flow and synthetic jets. In the present study,  $F^+=1.0$  corresponds to  $N=1.82$ , which means there are 1.82 bulges in the separation region at the same time.

As shown in Fig. 9, for  $F^+=0.2$ , the local separated flow is also forced downstream as the arrival of the bulge (Fig. 9(a) and Fig. 9(b)). However, the adjacent bulges are more distantly

spaced because of the lower actuation frequency, when the last bulge has passed through the separation region, the next one has not emerged. As a result, the separated flow bounces back, and the separation region returns to its original size at the rest phases (Fig. 9(c) and Fig. 9(d)), exhibiting a swinging motion in the actuation cycle.

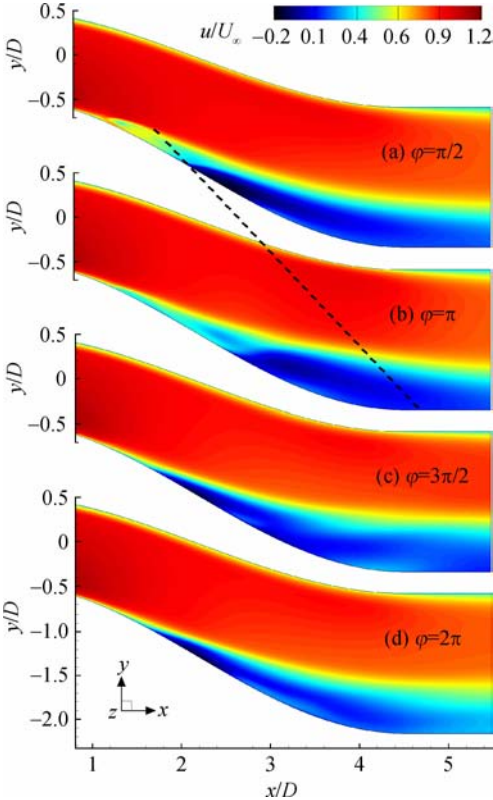


Fig. 9 Contours of normalized  $x$ -velocity  $u/U_\infty$  in a  $x$ - $y$  plane during an actuation cycle (at  $\Delta z=0.1725D$ ,  $F^+=0.2$ )

For the  $F^+=2.0$  case, the momentum flux produced by a single ejection (relates to the actuator amplitude) is insufficient to suppress the separated flow at such high frequency. As illustrated in Fig. 10, although the spacing between the adjacent bulges is smaller than other cases, no significant change in the separation region size at different phases.

From the above discussion, we can find that for a fixed momentum coefficient, the optimal frequency case can be understood as a balance between the momentum flux produced by a single ejection and the spacing of adjacent ejections. On one hand, the momentum flux must be large

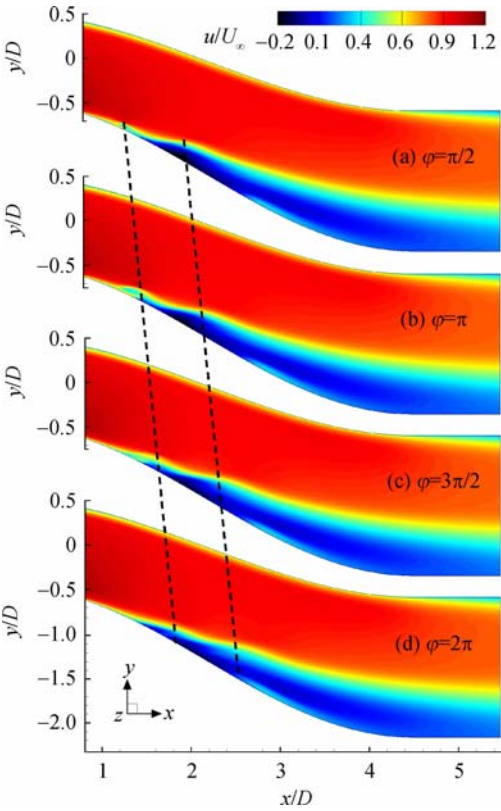


Fig. 10 Contours of normalized  $x$ -velocity  $u/U_\infty$  in a  $x$ - $y$  plane during an actuation cycle (at  $\Delta z=0.1725D$ ,  $F^+=2.0$ )

enough to force the separated flow downstream, on the other hand, when the bulge reaches the core of the separation region, a new bulge of the next cycle should be exactly formed at the slot. Thus the separated flow will not have enough time to bounce back, and the size of the time-averaged separation region will be largely reduced. Due to the limited ejection velocities of available synthetic jet actuators, it is particularly important to identify the optimal frequency with a low momentum coefficient, therefore, this finding has practical value in the separation control.

The  $x$ -component of skin friction coefficient  $C_{fx} \leq 0$  is used to determine the separation region,  $C_{fx} = \tau_{wx}/q_\infty$ , where  $\tau_{wx}$  is the  $x$ -component of wall shear stress. Fig. 11 presents the distribution of time-averaged  $C_{fx}$  on the lower surface, the white line indicates the edge of the separation region. For  $F^+=0.2$  and  $2.0$ , the reduction of separation length is limited. The  $F^+=0.5$  and  $F^+=1.5$  cases show some improvements, the separation length is decreased

by about 20%. As expected, a more remarkable reduction occurs at  $F^+=1.0$ , for which the separation

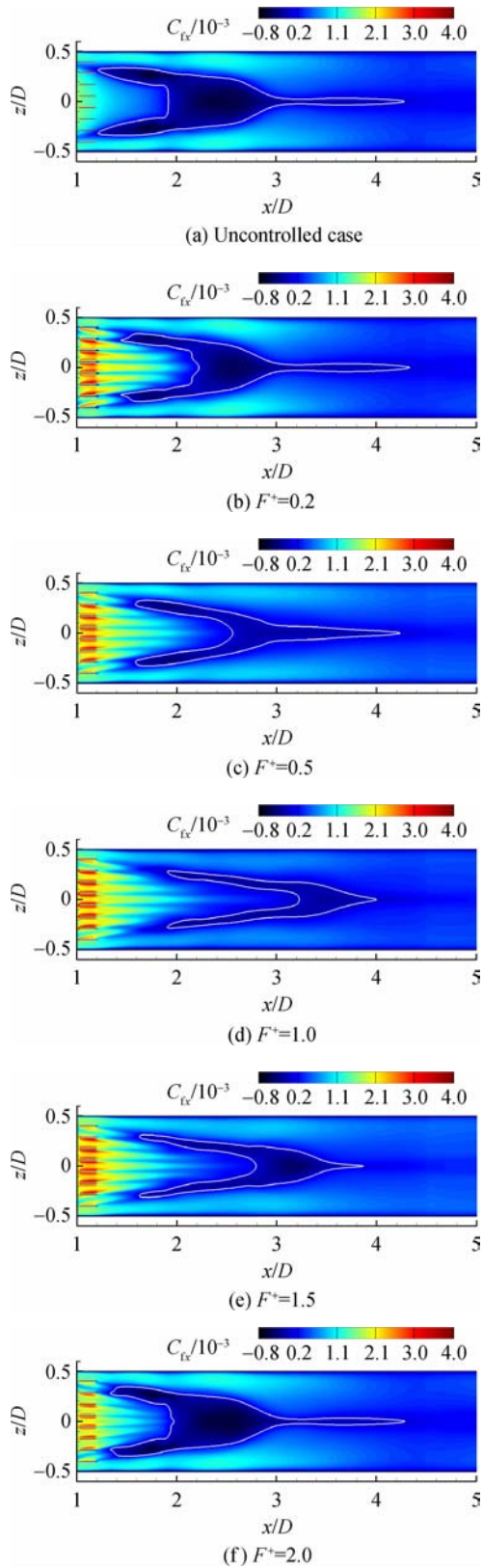


Fig. 11 Distribution of time-averaged  $x$ -component of skin friction coefficient  $C_{fx}$  on the lower surface

length is about 70% of the uncontrolled case.

The variation of normalized separation area  $S/S_u$  on the lower surface at different actuation frequencies is displayed in Fig. 12,  $S_u$  is the separation area of the uncontrolled case.  $S/S_u$  decreases for  $0.2 \leq F^+ \leq 1.0$ , damps to a minimum value of 0.51 at  $F^+ = 1.0$ , and then increases as the frequency increases. This variation demonstrates that there exists a narrow range of actuation frequency, in which effective separation control can be achieved.

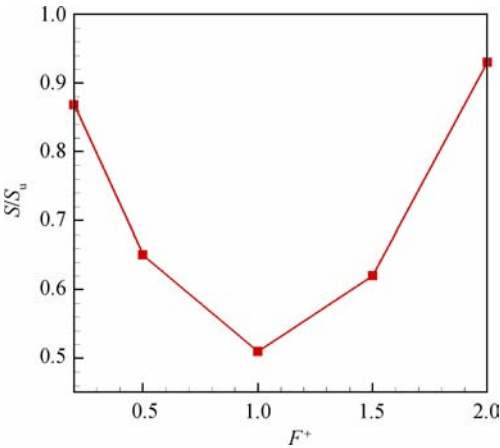


Fig. 12 Variation of normalized separation area  $S/S_u$  on the lower surface at different actuation frequencies

Figure 13 shows the time-averaged pressure coefficient  $C_p$  along the lower surface centerline. When the synthetic jets are activated, the pressure plateau of the uncontrolled case is reduced. It is noteworthy that the  $F^+ = 1.0$  case reveals a higher  $C_p$  slope than other cases in the plot, which indicates a higher resistance against separation and a higher pressure ratio.

The total pressure recovery and total pressure distortion are the other two important parameters for evaluating inlet performance. The distribution of time-averaged total pressure recovery  $\sigma$  at the S-duct outlet is illustrated in Fig. 14,  $\sigma = p_{t,out}/p_{t,\infty}$ ,  $p_{t,out}$  is the outlet total pressure,  $p_{t,\infty}$  is the entrance total pressure. As can be seen, there is a large low pressure region on the lower portion of the outlet for the uncontrolled case. The control effect is clearly more

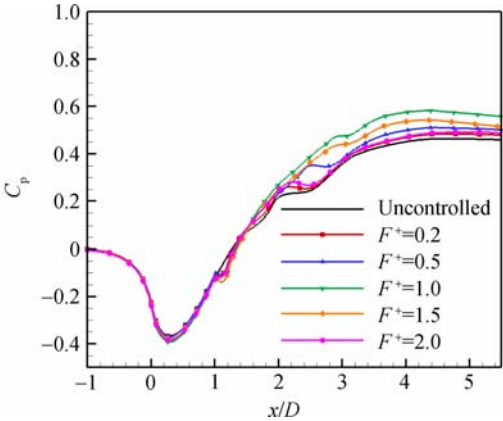


Fig. 13 Time-averaged pressure coefficient  $C_p$  along the lower surface centerline

pronounced for the  $F^+ = 1.0$  case, where the low pressure region is strongly depressed, and consequently the total pressure distortion is reduced and the total pressure recovery is improved.

Figure 15 compares the distributions of normalized time-averaged streamwise vorticity  $\omega_x D/U_\infty$  at the S-duct outlet between the uncontrolled and controlled cases ( $F^+ = 1.0$ ), the left half presents the uncontrolled case, and the right half presents the  $F^+ = 1.0$  case. Obviously, the streamwise vorticity is weakened on the lower portion by the auction, it indicates that the synthetic jets can also suppress the secondary flows while decreasing the separation, more research is needed to identify the causes of this suppression.

The performance parameters of the S-duct are listed in Table 1, where subscript  $u$  denotes the uncontrolled case, subscript  $u_0$  denotes the outlet of uncontrolled case.  $D_{c60}$  is the circumferential total pressure distortion descriptor and defined as  $D_{c60} = (p_{t,out} - p_{60,min})/q_{out}$ , where  $p_{60,min}$  is the minimum average total pressure in any  $60^\circ$  wedge at the outlet,  $q_{out}$  is the outlet dynamic pressure.  $S_{c60}$  is the swirl coefficient, which provides a measure of the intensity of the secondary flows, it is defined as  $S_{c60} = U_{60,max}/U_\infty$ , where  $U_{60,max}$  is the maximum average circumferential component of the transverse flow velocity in any  $60^\circ$  wedge at the outlet.  $F^+ = 1.0$  is identified as the optimal actuation frequency respect to the improvement of S-duct performance.

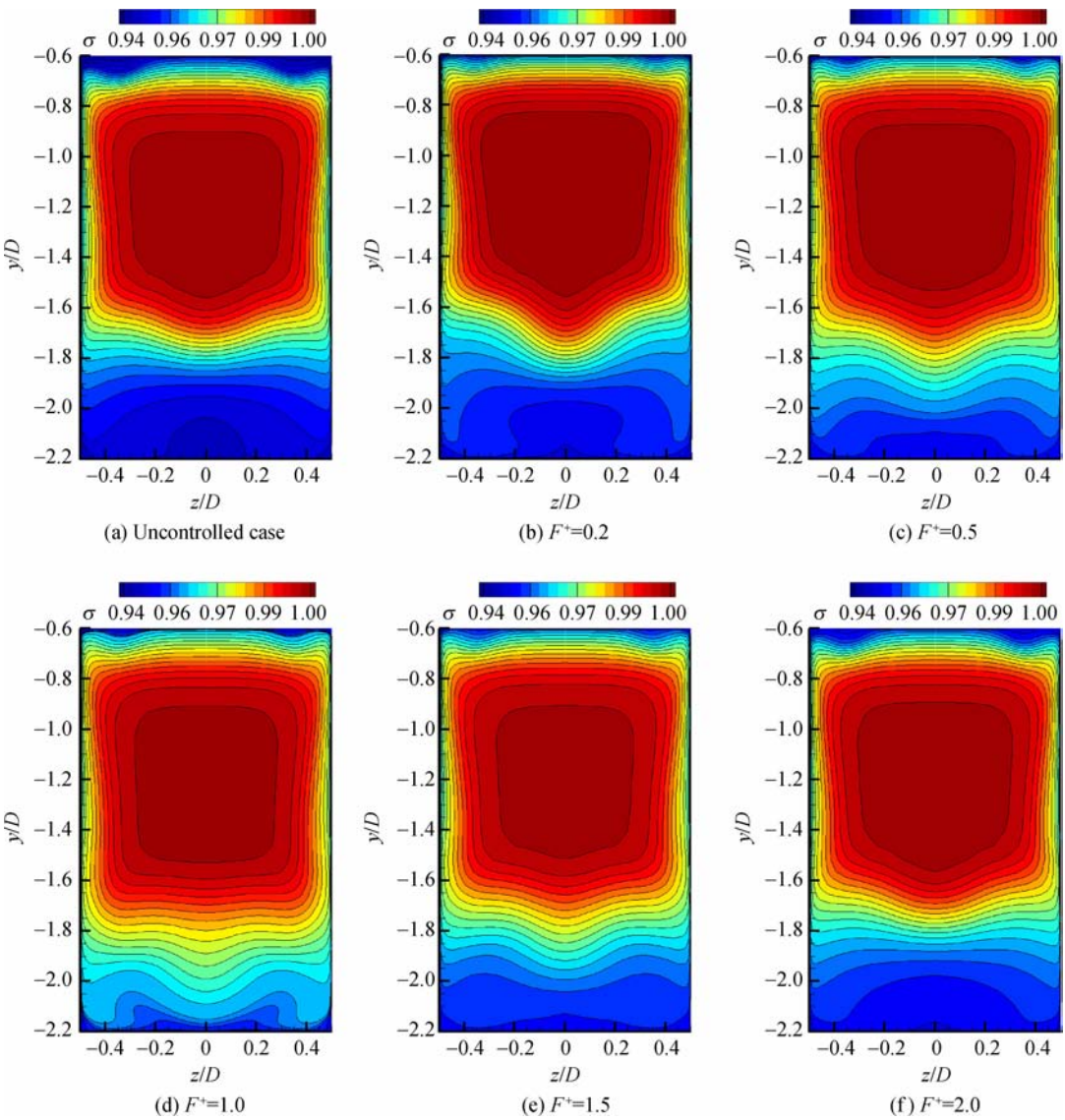


Fig. 14 Distribution of time-averaged total pressure recovery  $\sigma$  at the S-duct outlet

Table 1 Performance parameters of the S-duct

| Parameter                        | Uncontrolled | $F^+ = 0.2$ | $F^+ = 0.5$ | $F^+ = 1.0$ | $F^+ = 1.5$ | $F^+ = 2.0$ |
|----------------------------------|--------------|-------------|-------------|-------------|-------------|-------------|
| $C_{p,out}$                      | 0.467        | 0.482       | 0.517       | 0.562       | 0.528       | 0.498       |
| $(\Delta C_{p,out}/C_{p,u0})/\%$ | 0            | 3.21        | 10.71       | 20.34       | 13.06       | 6.64        |
| $\sigma$                         | 0.9784       | 0.9803      | 0.9819      | 0.9847      | 0.9828      | 0.9798      |
| $(\Delta\sigma/\sigma_u)/\%$     | 0            | 0.19        | 0.36        | 0.64        | 0.45        | 0.14        |
| $D_{c60}$                        | 0.549        | 0.461       | 0.437       | 0.324       | 0.423       | 0.516       |
| $(\Delta D_{c60}/D_{c60,u})/\%$  | 0            | -16.03      | -20.41      | -40.98      | -22.95      | -6.01       |
| $S_{c60}$                        | 0.0346       | 0.0325      | 0.0314      | 0.0219      | 0.0238      | 0.0302      |
| $(\Delta S_{c60}/S_{c60,u})/\%$  | 0            | -6.07       | -9.25       | -36.71      | -31.21      | -12.72      |

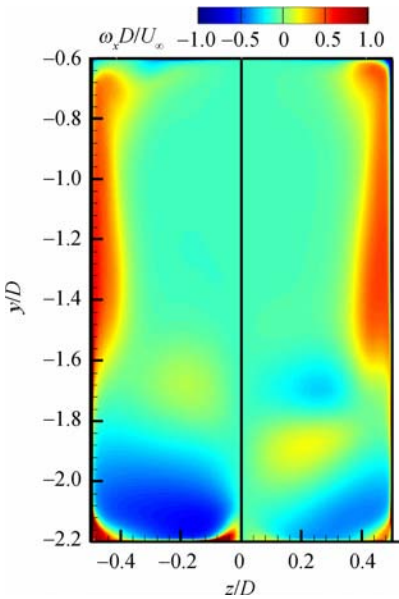


Fig. 15 Distribution of normalized time-averaged streamwise vorticity  $\omega_x D/U_\infty$  at the S-duct outlet  
(left half: uncontrolled, right half:  $F^+ = 1.0$ )

4 Conclusion

The effects of synthetic jet actuation frequency on the separated flow in a diffusing S-duct have been investigated. The results demonstrate that the control effect is significantly dependent on the momentum mixing enhancement between inside of the separated boundary layer and the outer flow. There exists a narrow range of actuation frequency, in which effective separation control can be achieved using synthetic jets. The dimensionless frequency  $F^+ = 1.0$  is identified as the optimal frequency in the present model, with a momentum coefficient of  $1.62 \times 10^{-3}$ , the separation area is decreased by about 46%, and the aerodynamic performance of the S-duct is also greatly improved compared to uncontrolled case.

Further analysis reveals that the choice of actuation frequency is mainly determined by the momentum flux produced by a single ejection and the spacing of adjacent ejections. For a fixed momentum coefficient, a excessively large momentum flux implies a large spacing, when the bulging structure generated by last ejection has passed through the separation region, the next

one has not emerged, thus the separated flow bounces back and the separation region returns to its original size quickly ( $F^+ = 0.2$  case). Nevertheless, if the momentum flux is insufficient, no significant change in the separation region size ( $F^+ = 2.0$  case). Therefore, the optimal frequency case can be understood as a balance between the two factors. In this study, the optimal frequency  $F^+ = 1.0$  corresponds to  $N = 1.82$ , which means there exist 1.82 bulges in the separation region at the same time. The results will be useful in developing effective separation control strategies based on synthetic jets.

Additionally, it is found that the synthetic jets can also suppress the secondary flows while decreasing the separation, more research is needed to identify the causes of this suppression.

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