

The influence of forcing frequency and amplitude to effectiveness of synthetic jets on laminar separation control

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Abstract

A synthetic jet actuator (SJA) is regarded to be effective if the separating bubble is eliminated in the control of boundary layer separation. One novel idea is to use the flow instability as internal energy to enhance the effectiveness of synthetic jets. To explore this idea, a three-dimensional large eddy simulation (LES) was performed and the influence of forcing frequency and amplitude to the SJA's effectiveness was investigated. The numerical model was verified by experimental results in a laminar separation zone in a boundary layer with adverse pressure gradient. The numerical results of the SJA's effectiveness were compared to identify the significance in changes made by varied forcing frequency at fixed forcing amplitude and by varied forcing amplitude at a fixed forcing frequency. Consistent with the wind tunnel experiments, LES results showed that the effectiveness of the SJA depends more on the forcing frequency than on the forcing amplitude. They support the inference from the experiments that the non-frictional Kelvin-Helmholtz (K-H) instability associated with the laminar separation is a source for enhancing the frictional Tollmien-Schlichting (T-S) instability which resists the laminar separation.

Introduction

Synthetic jet actuators have been under development since it was first recognized as acoustic screaming in 1980's [9]. Although they have shown great potential in active control of flow separation, SJAs are still not ready yet for products because issues such as compactness, weight and power density have not been addressed. As indicated in [5], in most laboratory demonstrations, the SJAs are either too big or too weak. The challenge is to develop an actuator that is not only small, light, robust and economic, but also capable to reach the control objectives.

A novel way to address the above issues is to use the instability of the base flow as internal energy resources to enhance the actuation of a micro SJA [2,6,7]. In the case of controlling laminar separation using SJAs, the actuation is to use the synthetic jet to trigger frictional T-S instability. This triggered T-S instability may be originally weak but can be enhanced by the non-frictional instability of the base flow until it becomes substantially powerful to effectively resist the laminar separation [7]. In this case, the effectiveness of the SJA may strongly depend on the instability and interaction of the jet and the baseline flow but not very much depend on the jet's performance in a quiescent condition.

Computational fluid dynamics (CFD) has been applied in developing SJAs. However, as Rumsey summarized in 2008, there had not been many published results for computation of synthetic jet in a *cross* flow since the CFD workshop organized by NASA in 2004 [13]. Most of the CFD work on synthetic jets, including the very recent ones like [14], has been focused on the

jet generation in a quiescent condition or its interaction with the flow adjacent to the jet. Few publications have reported numerical simulation of the interaction between the synthetic jets and the baseline flow to be controlled [1,3,4,10,11,15]. Allan et al [1] investigated the numerical simulation of a 2-D airfoil controlled by synthetic jets. They demonstrated the CFD model coupled with the model for rigid body motion. Parekh et al [11] numerically simulated the experiments of Honohan et al [8] that studied separation control on a thick airfoil using synthetic jet action. Their model successfully predicted the reattachment dynamics and the dependence of controlling reattachment on forcing frequency. Dandois et al simulated the cross flow downstream of the synthetic jet and numerically investigated the effect of forcing frequency of a SJA in controlling the separation in a backflow. They verified the models by comparing different numerical methods, URANS and LES [3] and LES and DNS [4]. You and Moin performed a 3D LES simulation of turbulent flow separation over a NACA 0015 airfoil and evaluated the effectiveness of SJAs on separation control. Ozawa et al developed a LES model for simulating a laminar separation bubble caused by adverse pressure gradient in a boundary layer and a SJA's effective resistance to this separation [10]. Their model was verified by wind tunnel experimental results.

As reviewed above, more work on investigating the interaction between the SJAs and the baseline flow is required to develop workable SJAs which are small, light, robust and economic. To explore the idea of using the flow instability to enhance the effectiveness of SJAs, this paper reports work on applying the verified LES model reported in [10] to simulating the interaction between a synthetic jet and a laminar separating flow. Various forcing frequencies and amplitudes were investigated to find their influence to the effectiveness of a SJA in control of a boundary layer laminar separation bubble.

Experimental background

The LES model aimed to simulate the boundary layer flow in the working section of a low speed wind tunnel which is schematically described in Fig. 1. A fairing was set above an aluminium flat plate with its angle adjustable for establishing the desired pressure gradient, similar to that of a diffusion compressor blade. The flat plate, located 1200 mm from the working section entrance, has a high quality surface finish and a leading edge with a negative incidence to avoid leading edge separation. The SJA was installed underneath the flat plate and on the streamwise centerline. The exit of the SJA was an orifice open to the boundary layer flow. In the experiment to be simulated, the streamwise velocity was measured using a hot wire anemometry in the boundary layer flow over the upper surface of the flat plate. The forcing voltage for the synthetic jets was $\pm 7.5V$, and forcing frequency was 100 Hz. More detailed information about the experiments can be found in [6,7].

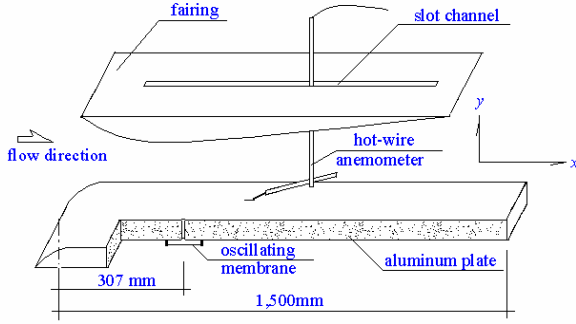


Figure 1 Schematic side view of the wind tunnel test section [6]

The SJA involved in the reported work consists of a cavity and an oscillating diaphragm. The jet is synthesized by oscillatory flow through a small orifice to a cavity. The flow is induced by a vibrating diaphragm which forms the bottom wall of the cavity. The axial centre of the orifice of the SJA was located 305 mm to the leading edge. The diameter of the orifice, d_o , was 0.5 mm and the membrane of this actuator, driven by a sine wave from a standard electrical signal generator, was a thin circular brass disc, 0.25 mm in thickness. In control of boundary layer laminar flow separation, the desired actuation of a SJA is to accelerate turbulence which prevents the flow from laminar separation.

Large eddy simulation

Large eddy simulation (LES) was applied and a commercial code, CFD-ACE, was used to solve the filtered Navier-Stokes. Figure 3 shows the computational domain. x corresponds to the streamwise direction, y the wall-normal direction and z the spanwise direction. The bottom of the computational domain is the upper surface of the flat plate in Figure 2. To facilitate comparison with the experiments, the dimensional length units are used. The dimensions of the computational domain are $L_x = 200\text{mm}$, $L_y = 60\text{mm}$ and $L_z = 90\text{mm}$ in streamwise, wall-normal and spanwise directions respectively. The domain is symmetric about the streamwise centreline at $z = 0$. The reference position, $x = 0$, $y = 0$ and $z = 0$, is the axial centre of the orifice at the exit of the SJA. The inlet of the computational domain is 20 mm upstream of the exit of the SJA, defined as $x = -20\text{m}$. The free stream mean velocity at the inlet was adjusted by the boundary layer thickness based Reynolds number Re_δ of approximately 500. Artificial-minute disturbance at the inlet was adopted by generating Gaussian Random numbers. The root-mean-square (RMS) of the disturbance was 1% of the free stream velocity at the inlet. The condition at the top boundary of the computational domain was defined by the static pressure data measured along the central streamwise line in the experiment.

By filtering the Navier-Stokes and the continuity equations in space, grid-filtered governing equation and Sub-grid scale stress (SGS) terms were produced. Dynamic Smagorinsky model was used for the approximation of SGS stress terms. The filtered Navier-Stokes equations were discretised in space using a hybrid scheme of the second-order central difference and first order upwind difference. As the project aimed to simulate the boundary layer interacting with a synthetic jet, the mesh in the boundary layer and in the adjacent area of the orifice of the SJA was finer. The mesh gradually became coarse with the distance further from the exit of the SJA. The reducing factor was 0.5. The total number of grids was 2,686,320 including 312 in x direction, 82 in y direction and 105 in z direction. ΔY^+ at the first node off the wall in the boundary layer was less than 0.6, and the corresponding ΔX^+ was less than 19 and ΔZ^+ less than 53. To test the grid independence, the mesh was refined with decreased ΔX^+ and ΔZ^+ . The characteristic parameters as the output showed

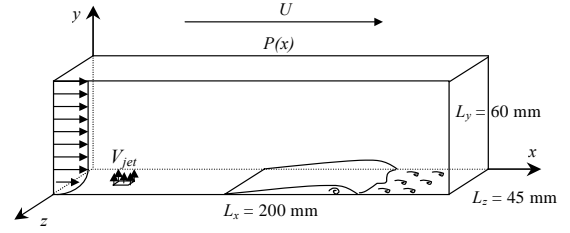


Figure 2 Schematic of computational domain

insignificant difference with the finer mesh. The forward and backward Euler and the second-order Crank-Nicolson methods were employed for time integration. The time step was set as $\Delta t = 0.0002\text{s}$ and the total number of time steps were 1600 in each run. The flow was considered as transient and the convergence criterion was 10^{-3} .

The LES simulation was verified by experiments described in the last section. Detailed comparisons were reported in [10]. Considering effective actuation of the SJA to resist the laminar separation, the numerical and experimental results are regarded to agree well.

Influence of forcing frequency to SJA's effectiveness

A SJA is recognized to be effective when its operation protects the flow from being separated from the wall in control of boundary layer laminar separation. To evaluate the effectiveness of a SJA, the laminar separation bubble needs to be visualized first. Then its removal by the SJA will be identified with the same visualization methods. One method is to visualize the laminar separation bubble is to indicate the height of the reverse-flow region by the point in the boundary layer where the streamwise velocity $u = 0$ which exists in an inflectional velocity profile [12]. In the present work, the position with $u = 0$ is used to identify the separation bubble, as it only exists in the boundary layer velocity profile when separation occurs. Figure 3 shows the laminar separation-short bubble viewed with $u_{\text{avg}} = 0$ by applying the above method. In Figure 3a is the separation bubble's 'edge' represented by $u_{\text{avg}} = 0$ on the x - y plane on the streamwise centreline $z=0$. In Figure 3b is the iso-surface of $u_{\text{avg}} = 0$ viewed on the x - z plane. The 'edge' of the separation bubble is on the averaged (x, y) positions with $u_{\text{avg}} = 0$.

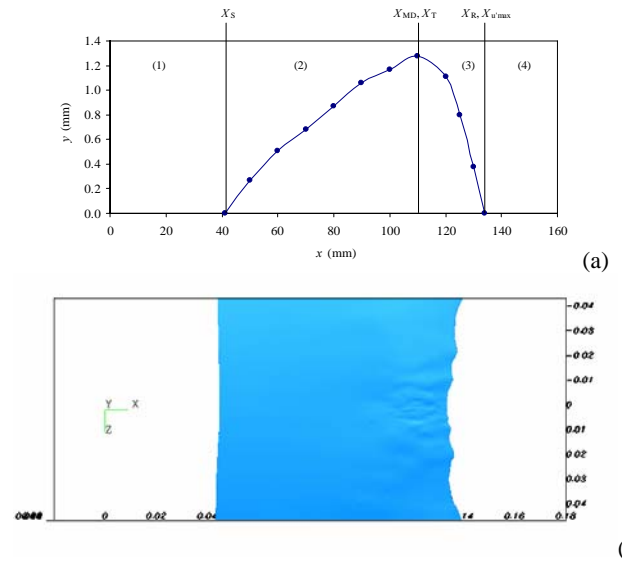


Figure 3 Laminar separation-short bubble viewed by positions with $u_{\text{avg}} = 0$, (a) on $z = 0$ plane, (b) on x - z plane.

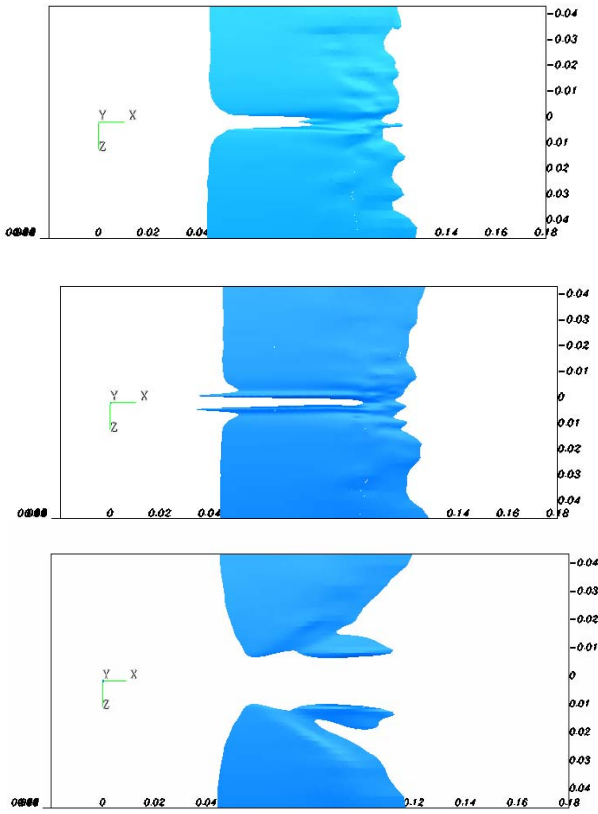


Figure 4 Iso-surfaces of the zero time-mean streamwise velocity, $u_{avg}=0$ at three forcing frequencies, from top to bottom, 800Hz, 400 Hz and 100 Hz, $V_{jet, max} = 6.0$ m/s.

In our previous experimental investigation, the forcing frequency in the lower frequency range of the T-S instability was effective but not in the higher frequency range. As defined in the last section, the effectiveness of a SJA is evaluated by that the laminar separation is eliminated when the SJA is switched on. To investigate the influence of the forcing frequency, numerical simulations with three forcing frequencies of 100 Hz, 400 Hz and 800 Hz, were performed. The maximum jet velocity at the exit of the SJA, $V_{jet, max}$, was 6.0 m/s. The iso-surfaces of the averaged positions with $u_{avg}=0$ in Figure 4 show the differences in the length and width of the eliminated bubble at these three forcing frequencies. In terms of the width of the separation bubble eliminated, it is obvious that the SJA driven at the forcing frequency of 100 Hz is more effective than that of 400 Hz and 800 Hz. Therefore, the length of the removed separation bubble with a forcing frequency of 100 Hz may be used as a reference for comparison, and the results of comparison are summarized in Table 1. As shown in Table 1, the lengths of the removed separation bubbles with the forcing frequencies of 400 Hz and 800 Hz are 86% and 43% respectively of that with a forcing frequency of 100 Hz. Using the width of the computational domain as a reference, the percentages of the minimum width of the removed separation bubble, measured at $x = 80$ mm, are 17.8% for 100 Hz, 3.1% for 400 Hz and 4.2% for 800 Hz.

The physics resulting in different SJA's effectiveness represented by the width and length of the removed separation bubble may be explained by the maximum fluctuating velocity, u'_{max} as shown in Figure 5. As the principle of using SJAs to control laminar separation is to accelerate the turbulence which is more capable of keeping the flow attached to the wall, u'_{max} is a useful indication of the effective action of a SJA. Figure 5 compares the maximum fluctuating velocity varying along the streamwise

direction when the SJA is switched off and on with three different forcing frequencies, 100 Hz, 400 Hz and 800 Hz, based on the same simulations as in Figure 4. As shown in Fig. 5, u'_{max} reaches its first peak value at a position between $x = 5$ mm and $x = 10$ mm, when the SJA is on. Following the first peak value, u'_{max} is damping to a minimum value even less than that of the baseline flow in the separation region when the forcing frequency is 400 Hz or 800 Hz. Only at the forcing frequency of 100 Hz, u'_{max} retains at a quite stable level between 1.2 m/s and 1.4 m/s in the original separation region ($x = 40$ -110mm) of the baseline flow. It shows that u'_{max} with a forcing frequency of 100 Hz has the greatest peak value, and that of 800 Hz has the least. Based on our previous experiments, it was hypothesized that the synthetic jet triggered the T-S instability which was then amplified by resonating with the K-H instability to accelerate the viscous transition and stop flow separation [6]. The T-S instability which was initially weak was enhanced by the K-H instability to become substantially strong and effective to resist separation. This means that, only at a 'right' forcing frequency which is in the lower range of T-S waves such as 100 Hz, T-S instability triggered by the synthetic jet would be amplified by the K-H instability. The simulation results at three forcing frequencies in Figures 4 and 5 positively support this hypothesis.

Forcing frequency (Hz)	Removed bubble length [#] (%)	Effective width* (%)
100	100.0	17.8
400	86.0	3.1
800	43.0	4.2

Table 1 Comparison of removed bubble lengths and widths at three forcing frequencies

[#]Bubble length divided by the bubble length in the baseline flow, at $z = 0$.

*Spanwise width of the eliminated bubble, divided by the width of the computational domain at $x=80$ mm.

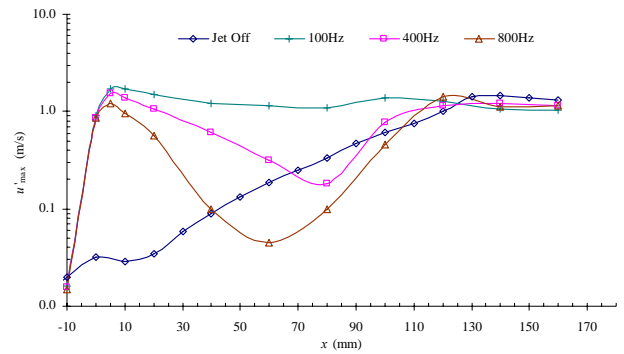


Figure 5 Variation of maximum fluctuating velocity with SJA off and on at three forcing frequencies, from top to bottom, 800Hz, 400 Hz and 100 Hz, $V_{jet, max} = 6.0$ m/s.

Influence of forcing amplitude to SJA's effectiveness

In the present study, the air inside the actuator was not simulated. Instead, the velocity along the centreline of the orifice of the synthetic jet, V_{jet} , was defined as an inlet to the computational domain at the exit of the SJA, and its maximum value, $V_{jet, max}$ represented the forcing amplitude. In order to investigate the influence of the forcing amplitude to SJA's effectiveness, $V_{jet, max}$ was varied from 1.5 m/s to 7.0 m/s at an interval of 0.5 m/s. The forcing frequency was fixed at 100 Hz based on the results of comparing three forcing frequencies as described above.

Simulation results of the separation zones visualized by the iso-surfaces of the averaged positions with $u_{avg} = 0$ (as that in Figure 4 but not shown here) indicated that the area of the eliminated bubble increased with the increased $V_{jet, max}$ before it reached a

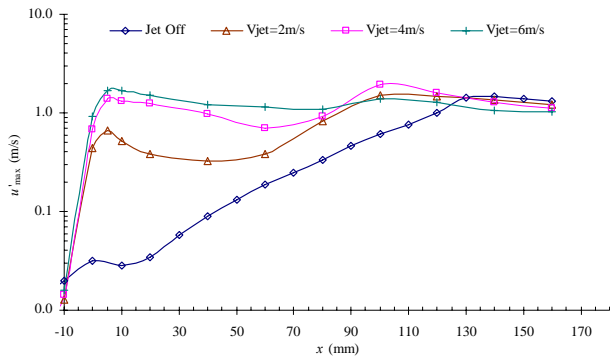


Figure 6 Variation of maximum fluctuating velocity with jet off and on at $z = 0$. Maximum jet velocity = 2.0 m/s, 4.0 m/s, 6.0 m/s. Forcing frequency = 100 Hz

certain value. The separation bubble was only partially eliminated when $V_{jet, max}$ was less than 4m/s. Further increasing $V_{jet, max}$ to be 5m/s and 6m/s did not show significant change in eliminating the separation bubble. This means that at a 'right' forcing frequency and with a sufficient distance between the SJA and the separation, a minimum jet velocity (or forcing amplitude) is required to ensure the SJA's effectiveness.

The maximum fluctuating velocity u'_{max} is used again to compare the effectiveness of the SJA at three maximum jet velocities. Figure 6 shows the variation of u'_{max} along the streamline centreline at three maximum jet velocities of 2.0 m/s, 4.0 m/s and 6.0 m/s, compared with the maximum fluctuating velocity with the jet off. As shown in Figure 6, u'_{max} at the maximum jet velocity of 6.0 m/s is steadier than that at the maximum jet velocities of 2.0 m/s and 4.0 m/s. In the region up to $x = 80$ mm, higher the maximum jet velocity, greater the maximum fluctuating velocity. However, the maximum fluctuating velocities at three different maximum jet velocities are all greater than that with the jet off. This shows that the SJA with lower $V_{jet, max}$ is less effective than that with higher $V_{jet, max}$ but may still be effective for eliminating partially the separation bubble. Compared with the results shown in Figure 5, the forcing frequency is more influential to the SJA's effectiveness than the maximum jet velocity is. This is also supporting our previous hypothesis based on experiments that the SJA might depend more on the forcing frequency than on the forcing voltage [7].

Conclusions

Three-dimensional LES was performed to investigate the influence of the forcing frequency and amplitude to the effectiveness of a SJA. The forcing amplitude was represented by the maximum jet velocity at the exit of the SJA. The effectiveness of the SJA was defined by elimination of the separation bubble. The iso-surface of $u_{avg}=0$ was used to visualize the separation zone and to identify the existence and disappearance of separation bubble. The maximum fluctuating velocity, u'_{max} , was used to show the development of the frictional instability triggered by the synthetic jet.

In consistence with the experimental results, numerical results showed that the SJA was effective when the forcing frequency was in the lower range of the T-S instability. They support the experiment-based hypothesis that the forcing frequency had stronger influence to the SJA's effectiveness than the forcing amplitude did. However, the results of investigating the influence of forcing amplitude indicate that a minimum value of the forcing amplitude is required to ensure the effectiveness of a SJA driven at a right forcing frequency. The results of simulation support the

idea of using the flow instability to enable a micro SJA to work effectively in control of laminar flow separation.

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