

## On Centerline Distributions of Velocity and Momentum in Synthetic Jet Actuator Flows

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### Abstract

An experimental investigation of the synthetic jets generated by piezoelectrically driven actuators with circular orifice is reported. The investigation aims to provide information for active control of boundary layer flows. Two different configurations of synthetic jet actuator, single- and dual-membrane, were investigated in conditions without cross flow. The mean and velocity and local momentum along the centerline of the jet are used to characterize the performance of the actuator. The effect of amplitude and frequency of the driving signals on the actuator's performance at Tollmien-Schlichting frequencies is examined, and the two types of actuators are compared.

### Introduction

Synthetic jet actuators have emerged as one of the most promising actuators for active control of boundary layer flows [1-9]. Different geometries have been proposed for synthetic jet design. As summarized in [4], the most widely used actuator geometries consist of an enclosed cavity with a small orifice on one face. Potential cavity shapes include square, rectangular and circular. The actuation methods include piezoelectric, electrostatic and electromagnetic and it is also possible to generate a synthetic jet using acoustic forcing. It has been found that the actuator outflow velocity scales with forcing amplitude and frequency, and several different kinds of jets can be obtained depending on the geometry and forcing characteristics. Nevertheless, the actuator characteristics which govern performance are largely unknown.

We have concentrated on synthetic jet actuators with circular cavity and orifice geometries and piezoelectric actuation. The broader scope of our efforts extends to control of boundary layer flows using these actuators. To this end, we wish characterize the performance of two different kinds of actuator: single and dual membrane. In particular, we wish to see how centerline distributions of mean velocity and momentum vary with forcing voltage and frequency and geometry. By making such a series of measurements, we can make intelligent decisions as to initial controller levels.

### Synthetic jet actuators and experiments

Figure 1 shows the two types of actuators considered here. For the single membrane actuator, the membrane makes up the bottom of the cylindrical cavity. The top of the cylindrical cavity is rigid and has an orifice in the center of the surface. For the dual membrane actuator, the two membranes construct the top and bottom of the cylindrical cavity, and they are symmetric about the orifice axis. The orifice exits through cavity sidewalls.

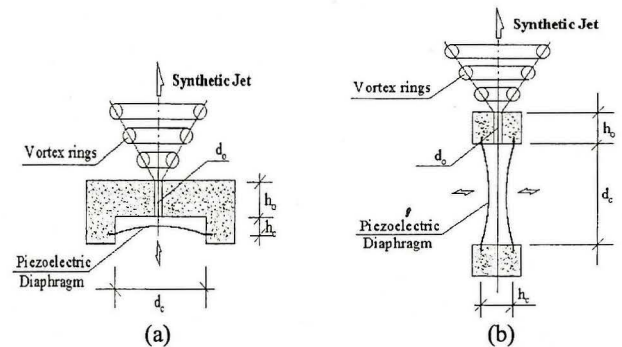


Figure 1. Schematic of synthetic jet actuator configurations. (a) single membrane; (b) dual membrane.  $d_0$  is the orifice diameter,  $d_c$  is the diameter of the membrane,  $h_0$  is the depth of the orifice and  $h_c$  is the maximum height of the cavity.

	$d_0$ (mm)	$h_0$ (mm)	$d_c$ (mm)	$h_c$ (mm)
Single membrane	0.8	6.0	40	1.25
Dual membrane	0.8	5.0	40	2.50

Table 1 Actuator dimensions

Table 1 shows the dimensions of the two actuators. The actuator membrane is a brass shim, held firmly at its perimeter, with the lowest resonant frequency of 900 kHz. A piezoceramic disc is bonded to the outside face of the membrane. In operation, the piezoceramic disc is driven by an electrical signal, such as a sine wave generated by a signal generator.

The velocity at the centerline of the jet was measured using a Dantec single-component hot wire anemometer. The sample rates were set at 3 kHz to 10 kHz and the sample size is 8192 ( $2^{13}$ ) to 16384 ( $2^{14}$ ) for each realization. The wire diameter and length are 5.0  $\mu\text{m}$  and 1.25 mm respectively. Considering that the length of the hot wire is greater than the orifice diameter of the actuator, the instantaneous velocity sensed by the hot wire is actually a spatial average of the velocity over the length of the hot wire [6].

The amplitude and frequency of the forcing sine wave signal were selected to examine their effect on the centerline mean velocity of the synthetic jet. The peak to peak amplitudes of the signals in our experiments were  $E_{p-p} \approx 5, 10$  and 20 volts. Three membrane forcing frequencies were chosen, 180 Hz, 290 Hz, and 1506 Hz,

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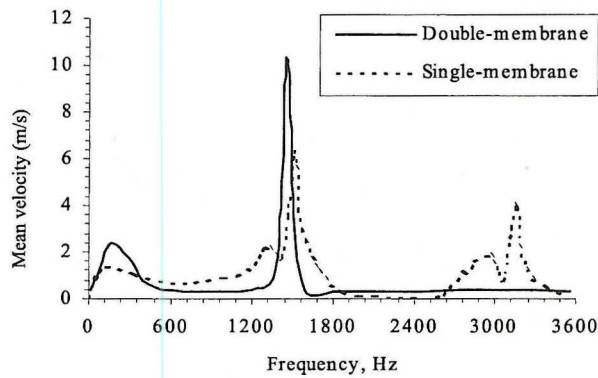


Figure 2 Mean centerline velocity varying with the forcing frequency,  $y/d_0 = 1.5$  or  $y = 1.2$  mm ( $y$  is the distance to the orifice)

the latter being used only in the single-membrane tests. The first two are in the range of the Tollmien-Schlichting (T-S) frequency associated with the boundary layer instability. Figure 2 shows the mean velocity at the centerline of the jet at 1.2 mm from the orifice, varying with the forcing frequency. The forcing amplitude applied was  $E_{p-p} \approx 20$  V. The maximum mean velocity at the centerline of the jet is 6.4 m/s at 1506 Hz for the single-membrane actuator, and 10.4 m/s at 1450 Hz for the dual-membrane actuator. As noticed in our experiments, the dual-membrane actuator's effect became very weak at the frequency of 1506 Hz which is the single membrane actuator's frequency for the maximum mean velocity. This may be due to that the oscillations of the two membranes were in phase, resulting in little compression in the cavity. In the low frequency bandwidth, a secondary peak velocity appears in the range of 100–300 Hz in Figure 2. From our ongoing project on the use of synthetic jets to modify boundary layer flows, we have noticed that the synthetic jets were more effective when the forcing frequency was in the range of T-S frequencies than others [10]. On the other hand, the noise generated by the synthetic jet actuators at high frequency ( $>1.0$  kHz) is audible and it is desirable to avoid such noise.

## Results and Discussion

Our ultimate goal of using synthetic jets is to actively control the boundary layer flow. The input of the control system will be the electrical signal driving the synthetic jet actuators, and the output will be the boundary layer properties. Ideally, the synthetic jets should be sufficiently effective inside the boundary layer region with minimum power input and maximum mass and momentum transform. Thus, the energy of the jet and the spatial and temporal distributions of the jet's energy are considerably important. The momentum flux of a turbulent jet,  $\dot{M}$ , is a function of the axial velocity and the fluctuating velocity of the jet [1]:

$$\dot{M} = 2\pi\rho \int_0^\infty r(u^2 + u'^2) dr \quad (1)$$

Where  $u$  is the axial velocity,  $r$  is the radial distance from the jet centerline,  $\rho$  is the density,  $u'^2$  is the sum of the pseudo-turbulence, due to the oscillation of the membrane, and the intrinsic turbulence.

The significance of the centerline velocity and fluctuating velocity has been identified in the recent work on synthetic jets. Mallinson et al reported that the measured and computed mean velocity profile exhibited a strong peak near the centerline and fell away with distance from the orifice in the spanwise direction [7]. Synthetic jets visualized using laser sheet and smoke techniques [3] show an axial pseudo-steady jet along the centerline, surrounded by vortex rings at certain  $Re_D$ .

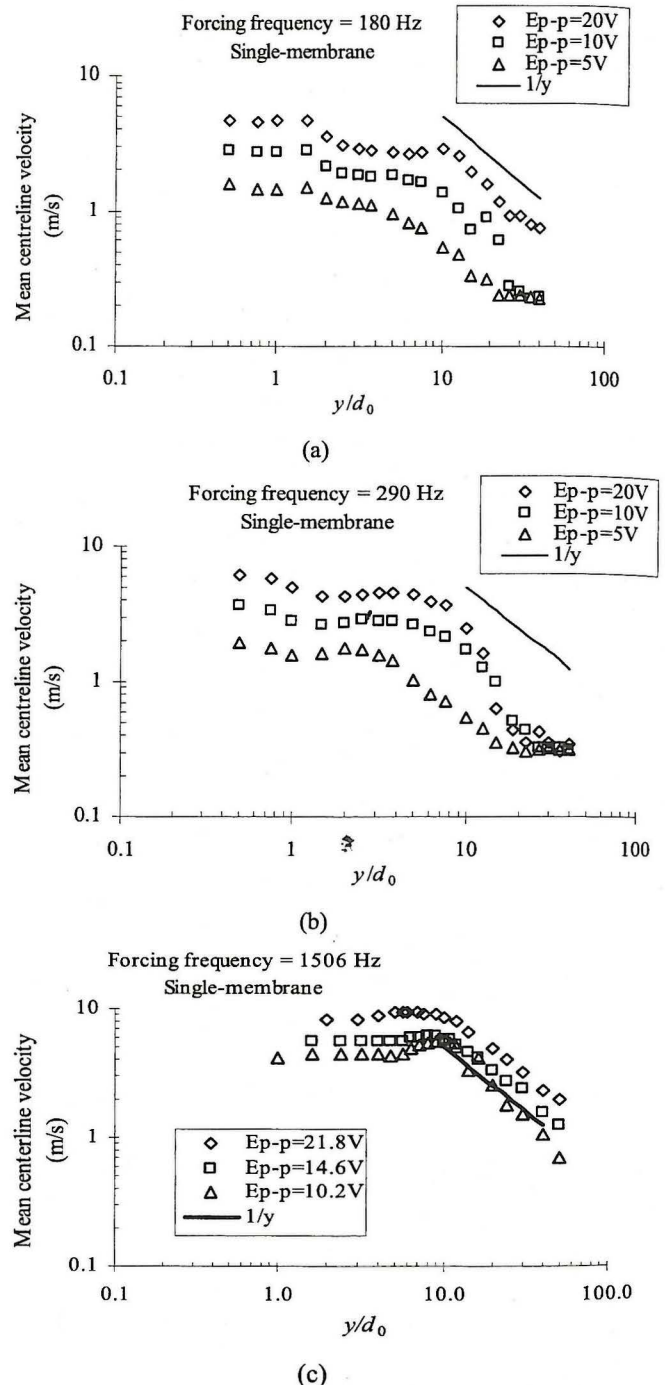
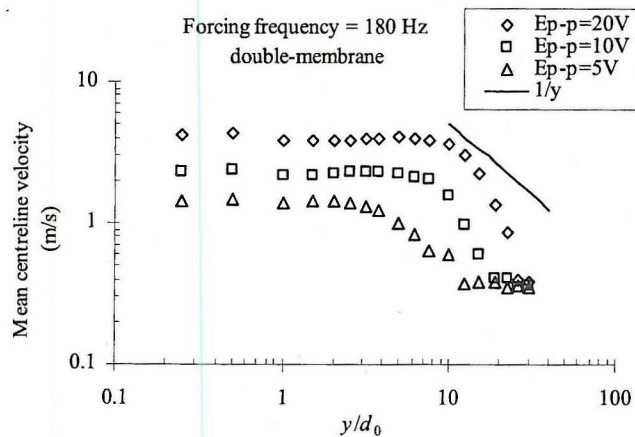
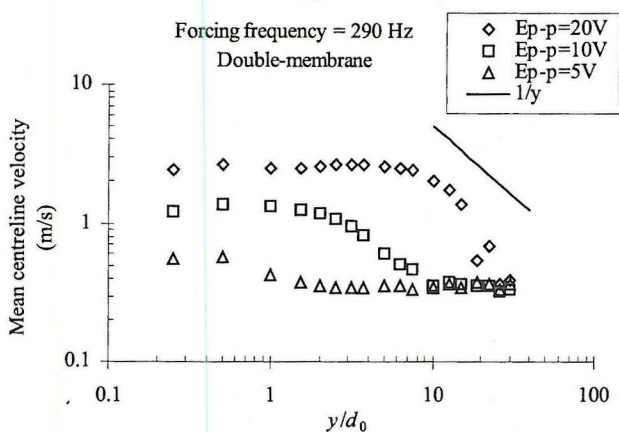


Figure 3 The mean velocity at the centerline of the jet, distributed over  $y/d_0$ , single-membrane synthetic jet actuator. (a) Forcing frequency = 180 Hz. (b) Forcing frequency = 290 Hz. (c) Forcing frequency = 1506 Hz

Understanding this axial steady jet may help us to understand the synthetic jet. The mean velocity and fluctuating velocity at the centerline of the synthetic jet have been chosen to characterize the energy of the synthetic jets. In the work of Rathnasingham and Breuer [8], the centerline mean velocity accelerated to a maximum at  $y/d_0 \approx 10$ , after which the mean centerline velocity varies as  $1/y$ . Here  $y/d_0$  is the distance from the orifice along the centerline of the jet,  $y$ , normalized by the diameter of the orifice,  $d_0$ . Recent results obtained by Mallinson et al were more substantial and evident in support of the hypothesized function of  $1/y$  for  $y/d_0 > 10$ . They also noted that, surrounded by vortex rings, a jet flow formed through the center of the synthetic jet acted as a convergent nozzle followed by a divergent diffuser [6].



(a)



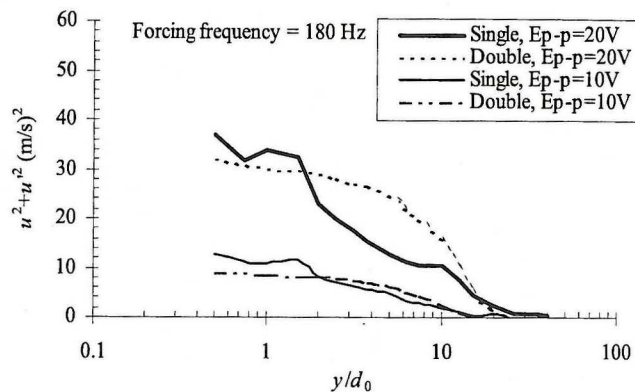
(b)

Figure 4. The mean velocity at the centerline of the jet, distributed over  $y/d$ , dual-membrane synthetic jet actuator. (a) Forcing frequency = 180 Hz. (b) Forcing frequency = 290 Hz.

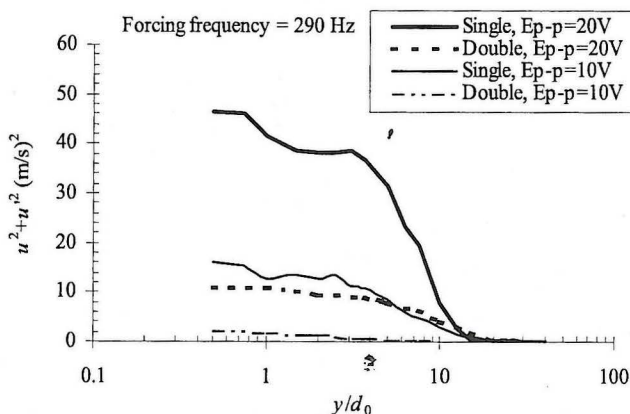
The control effectiveness of the synthetic actuator depends on both the level and spatial distribution of the jet energy. If the jet centerline is perpendicular to the flow direction, we prefer that the jet does not penetrate beyond the edge of the boundary layer and that actuation occurs at a position which maximizes the effectiveness in terms of controlling the flow. Therefore, our discussion will focus on the distributions of mean centerline velocity and momentum, and how they vary with changing amplitude and frequency of the driving signal.

Figure 3 shows the centerline mean velocity variation with  $y/d_0$  for the single-membrane actuator with forcing frequencies of 180, 290, and 1506 Hz. Here the 'mean' is the average of the velocity time series detected by the hot wire. As shown in Figure 3(c), the  $y/d_0$  positions for peak mean velocity are 6.4 when  $E_{p-p}$  is 21.8 V, 9.6 when  $E_{p-p}$  is 14.6 V and 10.5 when  $E_{p-p}$  is 10.2 V. The mean centerline velocity as a function of  $1/y$  remains well. The position for the peak mean centerline velocity at lower forcing frequency, while the similar forcing amplitudes are applied as shown in Figure 3(a) and 3(b), becomes closer to the orifice. It should be noted that close to the orifice, the jets may experience reversed flow, which causes rectification of the hot-wire signal. This is reflected in the initial decrease in velocity levels for low  $y/d_0$ . After this initial fall, the mean velocity rises to a peak value before decaying. In figure 3(a), this decaying looks more likely as  $1/y$ , consistent with earlier studies [6,7].

Figure 4 presents the mean centerline velocity distributions for the dual membrane configuration. Only forcing frequencies of



(a)



(b)

Figure 5 ( $u^2+u'^2$ ) varying with  $y/d_0$

180 and 290 Hz were examined here, to allow us to focus on actuators that have potential for controlling the boundary layer flows whose instability are characterized by T-S waves. The distributions have similar characteristics as those for the single membrane actuator, although the location of peak velocity is closer to the orifice, and the levels are somewhat lower for the dual membrane. The former may be due to the increased level of fluctuations, which gives rise to greater entrainment, in the case of the dual membrane actuator. It is not yet clear why the dual membrane actuator does not provide greater outflow velocities.

In previous work [7,8], the mean centerline velocity at a forcing frequency of 1450 Hz was seen to vary approximately as  $1/y$  for  $y/d_0 > 10$ , indicating that the jet flow became self-similar. At this forcing frequency, the synthetic jet was seen to be steady, self-similar, axisymmetric and turbulent. Most of these characteristics remain in the synthetic jets generated at lower forcing frequencies, except the self-similarity. As shown in Figure 3 (b) and 4, the mean centerline velocity is a function of  $1/y^n$ , here  $n$  looks more likely greater than 1.

As shown in equation (1), the total momentum flux of a turbulent jet is a function of  $(u^2+u'^2)$ , which may be termed the local momentum. As  $u$  and  $u'$  exhibit strong peak values in the center of the spanwise profile [7],  $(u^2+u'^2)$  along the centerline of the jet has also been used to evaluate the jet's energy distribution and effective region. Figure 5 presents the  $(u^2+u'^2)$  distributing over the jet centerline of the two configurations of actuators. As shown in Figure 5,  $(u^2+u'^2)$  of the single-membrane jet falls more quickly than that of the dual-membrane. However, with a forcing frequency of 290 Hz, the  $(u^2+u'^2)$  of the single-membrane synthetic jet is much greater than that of the dual-membrane, at

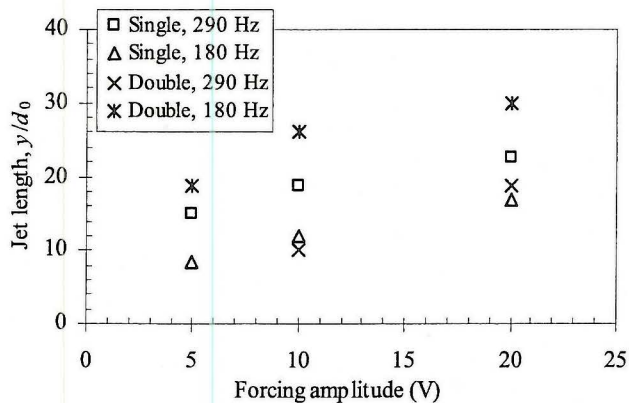


Figure 6 Variation of jet length with forcing amplitude

forcing amplitudes of 20 and 10 volts. When the forcing frequency is reduced to 180 Hz, the maximum  $(u^2+u'^2)$  values are similar for both actuators, but the dual-membrane jet's reduces more slowly until  $y/d_0$  is about 10.

If we define the effective jet penetration length of the synthetic jet by  $(u^2+u'^2) < 1.0$  (m/s)<sup>2</sup>, then the jet length varies in a range of  $y/d_0 = 8.3\sim 29.8$ , depending on the forcing amplitude and frequency, and the configuration of the actuator. As shown in Figure 6, the jet length increases in an approximately proportional manner with forcing amplitude. The single membrane seems to behave monotonically, whereas the dual membrane shows more effective at forcing frequency of 180 Hz than at 290 Hz. This information may prove useful when we take into consideration the system under control, that is, the specific boundary layer flow of interest.

As can be seen in Figure 3 and 4, the  $y/d_0$  value for peak mean velocity,  $(y/d_0)_{\text{peak}}$ , increases with driving voltage (except  $f=1506$  Hz). These observations are summarized in Fig. 7. If we consider the jet to behave as a convergent nozzle followed by a divergent diffuser [6],  $(y/d_0)_{\text{peak}}$  is the boundary of the 'nozzle' and the 'diffuser'. Therefore, the results in Fig. 7 may be explained as the length of the 'convergent nozzle' tending to increase with the amplitude of the driving signal. The mean centerline velocity remains a function of  $1/y^n$  in the 'divergent diffuser'. Figure 6 and 7 also show that the peak local momentum and peak mean velocity occur at different  $y/d_0$ .

### Conclusions

Synthetic jet actuators in single- and dual-membrane configurations were tested in the conditions without cross flow. The mean velocity and the local momentum along the centerline of the jet were used to characterize the performance of the actuator.

Based on the centerline distributions, the performance of the dual membrane actuator is not significantly better than that of the single membrane. In fact, the single membrane actuator looks more effective than the dual membrane at lower driving frequencies, which are the selected T-S frequencies.

The non-dimensional centerline position for the peak mean centerline velocity is in a range of  $0.5 < y/d_0 < 10.5$ , depending on the configuration of the synthetic jet actuator, and the forcing amplitude and frequency. By using  $(u^2+u'^2)$  to approximate the synthetic jet's energy, it was noticed that the effective jet length, defined by the centerline position with a minimum  $(u^2+u'^2)$ , is in a range of  $8 < y/d_0 < 30$ . Considering the use of synthetic jet actuators in boundary layer flow control, it is estimated that the

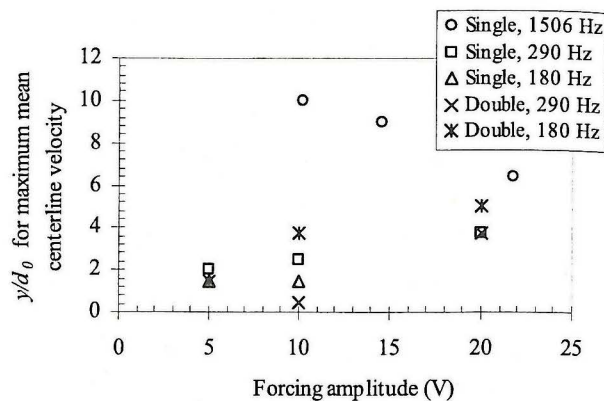


Figure 7 Position of the peak mean centerline velocity

jets generated by the tested actuators be effective within the boundary layers, at zero pressure gradient, for the flows with  $Re_{\delta 1} = 600 \sim 1 \times 10^4$ .

The synthetic jets generated with lower forcing frequencies ( $< 0.5$  kHz) remain self-similarity for  $y/d_0$  greater than a certain number, as has been noticed in several previous studies of synthetic jets generated at a higher forcing frequency ( $> 1$  kHz). However, the function representing this similarity is extended to  $1/y^n$  ( $n \geq 1$ ) rather than  $1/y$ .

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