TECHNICAL NOTE

Turbulence suppression in an elliptic jet

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Some instability characteristics in elliptic jets are presented. Turbulence suppression has been observed in an elliptic jet (aspect ratio, 2:1) under controlled excitation for Strouhal number St_θ between approximately 0.005 and 0.024. Results over a range of excitation level from 0.25–9 percent for $St_\theta = 0.012$ and 0.017 show that low excitation level is as effective as high excitation level in suppressing turbulence.

Keywords: turbulence suppression; elliptic jet; instability

Introduction

Jets under controlled excitation have received considerable attention in the past decade primarily for two reasons. Firstly, the perturbation introduced into the flow may enhance the naturally occurring large-scale coherent structures that can be studied using conditional sampling techniques to provide an improved understanding of fundamental phenomena such as the structure of turbulence, shear-layer instability, and natural entrainment processes. Secondly, the perturbation introduced at any arbitrary frequency and amplitude may produce nonnaturally occurring structures that subsequently influence the characteristics of the flow field. In cases in which such perturbations enhance mixing and entrainment, they have important implications in practical application areas such as fluidics, combustion, and thrust-augmenting ejectors for VSTOL aircraft. Increase in jet entrainment can be achieved by active or passive means. If a jet is excited at frequencies other than the instability frequency of the exit shear layer, the increase in entrainment downstream of the nozzle is often accompanied by an increase in turbulence intensity, as discussed by Lai.[1] On the other hand, jet entrainment can be increased by passive means such as manipulation of the nozzle geometry. As demonstrated by Ho and Gutmark[2] and Quinn,[3] the entrainment of a low aspect ratio elliptic jet is several times greater than that of a circular or plane jet, due to the self-induction of asymmetric coherent structures. Hussain and Husain,[4] in their studies of the instability characteristics in an elliptic jet (with an aspect ratio of 2:1), have shown that jet entrainment can be further increased through controlled excitation.

Zaman and Hussain[5] demonstrated that turbulence could be suppressed by controlled excitation and that maximum turbulence suppression occurred in a number of free shear flows (circular jets, plane jet, and a single-stream plane mixing layer) at a Strouhal number $St_\theta = f\theta_e/U_e$ of around 0.017, where θ_e is the exit momentum thickness and U_e is the free stream velocity. Nallasamy and Hussain[6] showed that at high amplitudes of excitation, maximum turbulence suppression occurs at St_θ higher than 0.017. The objectives of this note were to report the influence of Strouhal number on turbulence suppression in an elliptic jet and the effects of amplitudes of excitation on turbulence suppression.

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Experimental conditions

The elliptic jet facility consists of two settling chambers connected in tandem. A loudspeaker attached to the first settling chamber produces longitudinal plane-wave excitations at the nozzle exit and any possible asymmetry induced by the speaker arrangement in the first chamber is eliminated by the second settling chamber. A contoured elliptic nozzle with an aspect ratio 2:1, a contraction ratio of 25:1, and an equivalent diameter D_e of 50.8 mm was used. Here $D_e = 2\sqrt{ab}$ is defined as the diameter of a circular jet with a momentum flux equal to that of an elliptic jet of exit semi-major and semi-minor axes a and b, respectively. The nozzle was specially contoured to eliminate the effect of the azimuthal variation of exit momentum thickness. As the resonance frequency of the excitation system was limited, the experiments had to be conducted at a fixed excitation frequency and the exit speed had to be varied to cover a range of Strouhal number St_θ from 0.003–0.035. Streamwise velocity and turbulence intensity data were obtained in both the minor-axis and major-axis planes with a single 5-μm tungsten hot-wire, which was operated at an overheat ratio of 1.4 with DISA 55 M constant temperature anemometer. The hot-wire signal was linearized. Data acquisition and probe traverses were performed on line with a Masscomp computer. Power spectra of the streamwise velocity fluctuations were obtained using an Ono Sokki CF-920 FFT signal analyzer.

Results and discussion

The exit streamwise velocity fluctuation for the unexcited jet is less than 0.1 percent of the exit velocity. The exit momentum thickness of the shear layers in both the minor-axis and major-axis planes have been measured and agree with each other to within 5 percent. The shape factor, defined as a ratio of the displacement thickness to the momentum thickness, for the range of Reynolds numbers covered in the experiments is about 2.6.

Turbulence suppression in the minor-axis and major-axis planes

Based on the studies of Zaman and Hussain,[5] maximum turbulence suppression for circular and plane jets occurs at around $St_\theta = 0.017$. Since $St_\theta = 0.012$ corresponds to maximum amplification of a disturbance and $St_\theta = 0.017$ corresponds to the case of maximum amplification rate, these two conditions were chosen to excite the jet with an excitation level (u'_f/U_e) of 0.5 percent measured at the jet exit centerline. Here f is the excitation frequency. Traverses of streamwise velocity fluctuation have been made in both the minor-axis and major-axis planes at $x/D_e = 1$ and 4 for the unexcited jet (u'_{un}) and excited jet (u'_{ex}), respectively.

The streamwise velocity fluctuation profiles, expressed as u'_{ex}/u'_{un}, in the minor-axis plane at $x/D_e = 1$ is shown in Figure 1a. It can be seen that the main contribution to the streamwise velocity fluctuation for $St_\theta = 0.012$ is due to the passage of large-scale structures with a frequency of $f/2$ while large-scale structures with a frequency of $f/4$ appear to be dominant for $St_\theta = 0.017$. These results indicate that two pairings of the large-scale structures have occurred by $x/D_e = 1$ for $St_\theta = 0.017$ while only one pairing has occurred for $St_\theta = 0.012$. The streamwise fluctuation levels for both excitation conditions are higher than those for the unexcited jet. By $x/D_e = 4$, the contribution to the streamwise velocity fluctuation in the minor-axis plane by the passage of large-scale structures is hardly detectable, as shown in Figure 1b. In fact, $x/D_e = 4$ for this jet is the end of the potential core, and the breakdown of the large-scale structures has occurred so that the contribution of the streamwise velocity fluctuation here is dominated by small-scale turbulence structures. Figure 1b shows that turbulence suppression (expressed as u'_{ex}/u'_{un}) has been achieved over 90 percent of the jet.

The streamwise velocity fluctuation profiles (u'_{ex}/u'_{un}) in the major-axis plane have been plotted in Figures 2a and b, respectively, for $x/D_e = 1$ and 4. The trend of these profiles is similar to those exhibited in the minor-axis plane shown in Figures 1a and b. The source of streamwise velocity fluctuation at $x/D_e = 1$ is due to the passage of large-scale vortex structures while turbulence suppression in the major-axis plane has been observed for over 90 percent of the jet by $x/D_e = 4$.

Effect of St_θ on turbulence suppression

In order to study the influence of St_θ on turbulence suppression (i.e., $u'_{ex}/u'_{un} < 1$), the turbulence intensity at the centerline for $x/D_e = 4$ was measured for the unexcited jet (u'_{un}) and for the excited jet (u'_{ex}) at 620 and 1050 Hz, with excitation levels (u'_f/U_e) of 0.5 and 1 percent measured at the nozzle exit centerline. The nozzle exit velocity was varied to give a range of Strouhal number from 0.003–0.034. The variation of u'_{ex}/u'_{un}

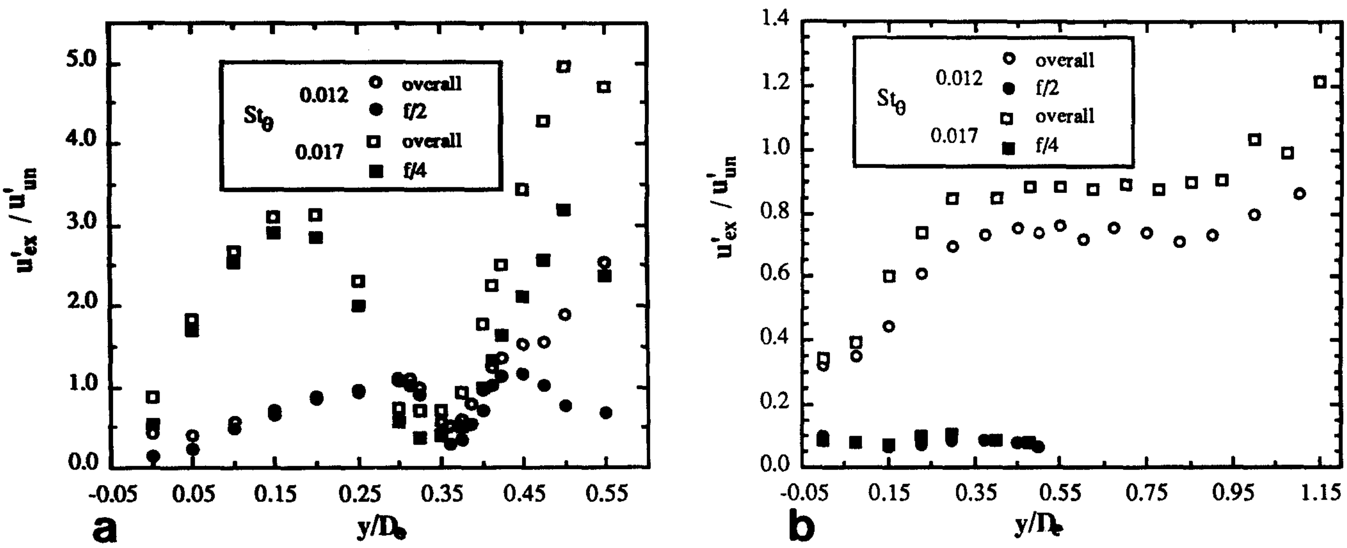

Figure 1 (*a*) Normalized streamwise velocity fluctuation levels in the minor-axis plane at $x/D_e = 1$. (*b*) Normalized streamwise velocity fluctuation levels in the minor-axis plane at $x/D_e = 4$

Notation

a	Semi-major axis of an elliptic nozzle
b	Semi-minor axis of an elliptic nozzle
D_e	Equivalent diameter, $2\sqrt{ab}$
f	Frequency (H_2)
U_e	Nozzle exit velocity
u'_{ex}	Streamwise velocity fluctuation under controlled excitation
u'_{un}	Streamwise velocity fluctuation for the unexcited jet
St_θ	Strouhal number based on nozzle exit momentum thickness, $f\theta_e/U_e$
x	Streamwise coordinate measured from nozzle exit
y	Transverse coordinate measured from nozzle exit
θ_e	Nozzle exit shear layer momentum thickness

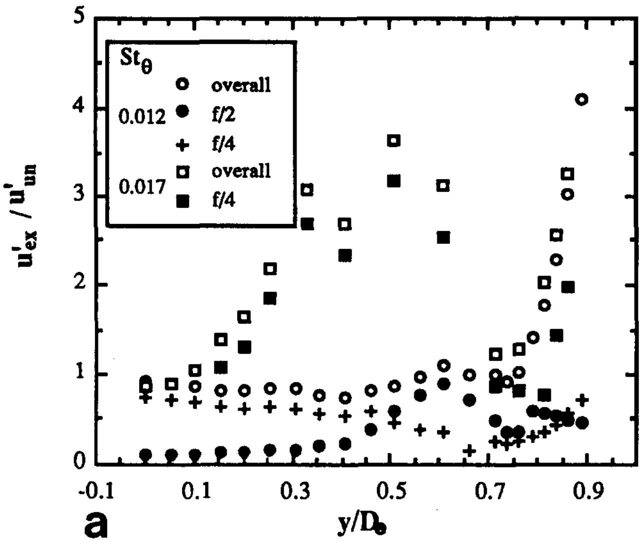

Figure 2(a) Normalized streamwise velocity fluctuation levels in the major-axis plane at $x/D_e = 1$

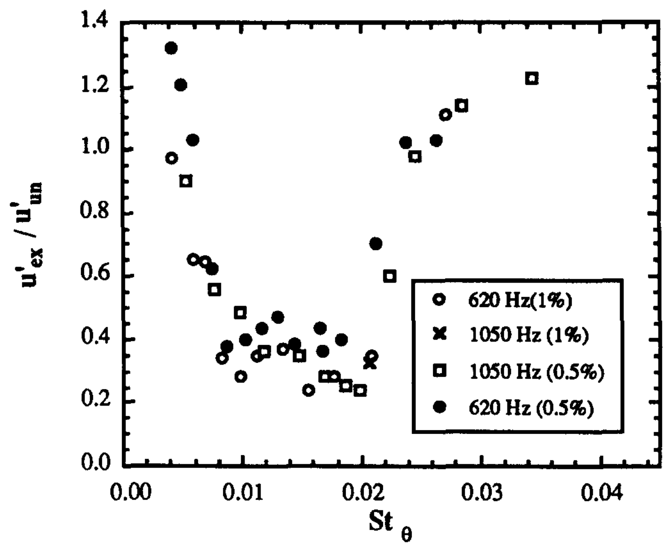

Figure 3 Variation of turbulence suppression with St$_\theta$

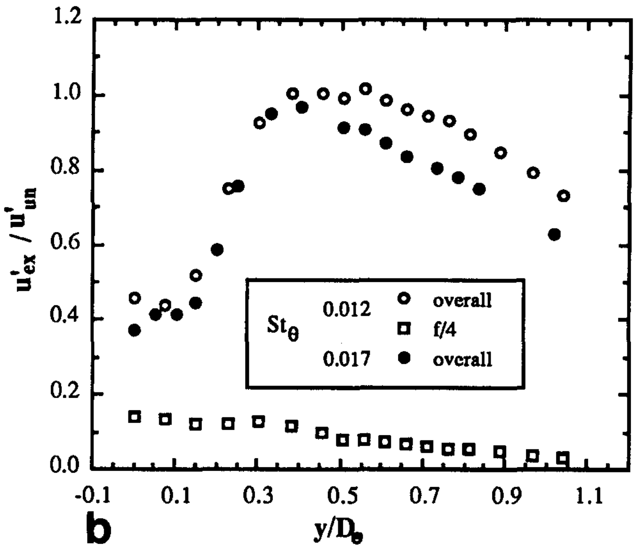

Figure 2(b) Normalized streamwise velocity fluctuation levels in the major-axis plane at $x/D_e = 4$

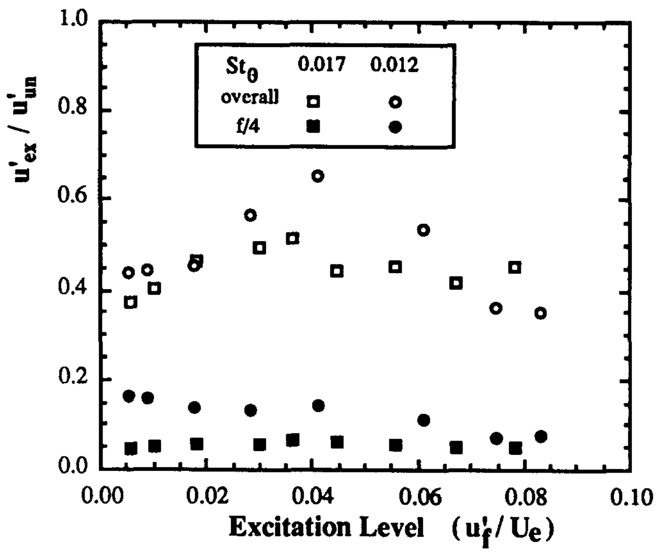

Figure 4 Variation of turbulence suppression with excitation level

with Strouhal number St$_\theta$ (based on exit momentum thickness) is plotted in Figure 3. It can be seen that for the excitation levels tested, turbulence suppression of the order of 50 percent has been achieved for $0.008 \leqslant St_\theta \leqslant 0.022$, and turbulence intensity will be increased if the excitation is introduced at $St_\theta < 0.004$ or $St_\theta > 0.24$.

Effect of excitation level on turbulence suppression

The variation of turbulence suppression at the centerline of the jet for $x/D_e = 4$ as a function of the excitation level (u'_f/U_e) is plotted in Figure 4 for $St_\theta = 0.012$ and 0.017. Although there are some variations in the magnitude of turbulence suppression obtained for the two different conditions, the trend is about the same and indicates that low excitation level (0.5 percent) is just as effective as high excitation level in suppressing turbulence. This is perhaps due to saturation of large-scale structures at the higher excitation levels. Also shown in Figure 4 is the streamwise velocity fluctuation level at f/4 (f is the excitation frequency), indicating that the passage of large-scale structures is not a dominant factor in contributing to the streamwise velocity fluctuation at $x/D_e = 4$.

Conclusions

It has been shown here that, just as in circular and plane jets, turbulence suppression has been observed in an elliptic jet with an aspect ratio of 2:1 for $0.004 \leqslant St_\theta \leqslant 0.024$. It appears that small amplitude (0.5 percent) of excitation is as effective as large amplitude of excitation (8 percent) in suppressing turbulence perhaps due to saturation of large-scale vortex structures.

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