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SOME INSTABILITY CHARACTERISTICS IN JETS

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ABSTRACT

Some instability characteristics in tube jets and elliptic jets are presented. For tube jets, the preferred mode, deduced from the frequency spectra of the streamwise velocity, was characterized by the Strouhal number St. For a fully-developed laminar exit condition, St increases with Reynolds number Re and approaches an asymptotic value of about 0.5 while for a fully-developed turbulent exit condition, St is virtually independent of Re and attains a value of about 0.4 at the end of the turbulent core. 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% to 9% for $St_\theta = 0.012$ and 0.017 show that low excitation level is as effective as high excitation level in suppressing turbulence.

INTRODUCTION

The instability characteristics in shear flows and their development in time and space are important for understanding the evolution of coherent structures, the breakdown of laminar flow and its transition to turbulent flow. In this paper, some results obtained in tube jets and in an elliptic jet with an aspect ratio of 2:1 will be discussed.

In their studies of axisymmetric jets subjected to controlled excitations, Crow & Champagne (1971) showed that there exists a 'preferred' frequency at which an axisymmetric disturbance receives maximum amplification in the entire jet column. The frequency of the 'preferred' mode corresponded to a Strouhal number $St_D = fD/U_c$ of about 0.3, where f is the excitation frequency, D is the jet diameter and U_c is the jet exit speed. Hussain & Zaman (1981) distinguishes two types of jet instabilities, namely the shear layer mode and the preferred mode. The shear layer arises from the instability of the initial shear layer where the frequency scales with shear layer thickness while the preferred mode is a global instability of the entire jet column where the frequency scales with jet diameter. Extensive studies of instability characteristics have been reported on both axisymmetric and plane jets with thin exit shear layers (see, for example, Hussain & Zaman(1981), Foss & Korschelt (1983)), each of which exhibits the shear layer mode as well as the preferred mode. However, recent studies by Petersen & Samet (1988) have shown both experimentally and numerically that the preferred mode is a shear layer instability and scales with local shear layer thickness.

Theoretical and numerical studies of instability characteristics of axisymmetric jets with parabolic exit velocity profiles (see, for example, Batchelor & Gill (1962), Kambe (1969)) have shown that such a jet is stable against axisymmetric disturbance but unstable against azimuthal disturbance. However, complementary experimental data are lacking. An axisymmetric jet issuing from a pipe with a fully-developed laminar velocity profile, hereinafter referred to as a 'tube' jet, will yield a parabolic profile. For this laminar exit condition, the shear layer is thick so that the relevant length scale is the tube diameter. On the other hand, if the exit condition from a tube jet is turbulent, the shear layer is thin so that there are two relevant length scales, namely, the shear layer thickness for the initial shear layer and the tube diameter for the jet column. The objective of the tube jet study was to determine the preferred mode for fully-developed laminar and turbulent exit conditions.

Hussain & Zaman (1981) demonstrated that maximum turbulence suppression due to controlled excitation occurred in a number of free shear flows (circular jets, plane jet, and a single-stream plane mixing layer) at a Strouhal number $St_\theta = f\theta/U_c$ of around 0.017, where θ_e is the exit momentum thickness and U_e is the free stream velocity. Nallasamy & Hussain (1989) showed that at high amplitudes of excitation, maximum turbulence suppression occurs at St_θ higher than 0.017. Instability characterisitcs in an elliptic jet with an aspect ratio of 2:1 in terms of preferred mode, spatial growth rates and initial conditions have been reported by Hussain & Husain (1989). The objective here was to document turbulence suppression in this elliptic jet and to study the effects of amplitudes of excitation on turbulence suppression.

EXPERIMENTAL CONDITIONS

Tube Jet

For the studies of the preferred mode of a tube jet, three pipes with diameter (D) 3.18 mm, 6.35 mm and 12.7 mm and the corresponding length/diameter ratios of 576, 1152 and 2304 were used. Compressed air was supplied through an air filter, a pressure regulator which adjusted the jet exit speed and a plenum chamber. The experiments covered both fully-developed laminar and turbulent exit conditions with Reynolds number ranging from 200 to 20,000. A single 4μm tungsten hot-wire at an overheat ratio of 1.5 operated with DISA 55M constant temperature anemometer and linearizer was used to obtain the mean streamwise velocity and turbulence intensity. Data acquisition and probe traverses were performed on line with a Masscomp computer. Power spectra of the streamwise velocity fluctuations were obtained using an FFT signal analyzer (Ono Sokki CF-920).

Elliptic Jet

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 jet 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 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 to 0.035. Streamwise velocity and turbulence intensity data were obtained in both the minor-axis and major-axis planes with a single 4μm tungsten hot-wire.

RESULTS AND DISCUSSIONS

Tube Jet

Fully-developed laminar exit condition. The velocity fluctuation at the jet exit for all test conditions is less than 0.3% of the centre-line velocity. The mean velocity profiles at 0.5D from the exit for various Reynolds numbers (based on average jet exit speed $\bar{U}_e$ and the tube diameter) and tubes are shown in Figure 1 and compare well with a parabolic profile, thus indicating that fully-developed laminar exit conditions have been attained at the jet exit.

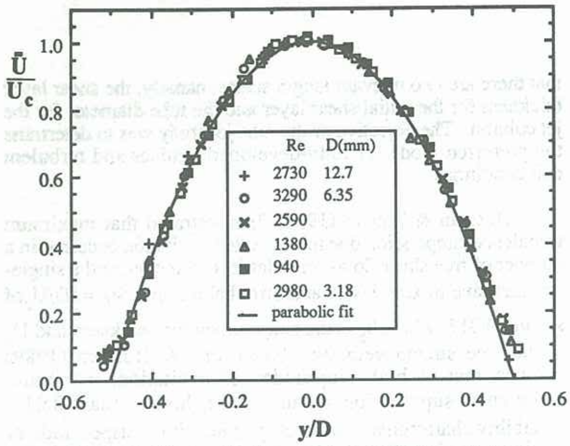

Figure 1 Mean velocity profiles at 0.5D from jet exit.

Power spectra of the streamwise velocity fluctuation u' for the 3.18 mm tube at location (15D, 0.3D) are shown in Figure 2 for various Reynolds numbers. The spectral humps in Figure 2 correspond to energetic instability waves. Though not shown here, it has been found that the mean frequency of the spectral hump is independent of radial locations but decreases with increasing streamwise distance x. Consequently, the preferred mode for a tube jet with fully-developed laminar exit condition is determined from the mean frequency of the spectral hump obtained at the end of the laminar core where the centre-line velocity has decreased to 95% of its value at the jet exit.

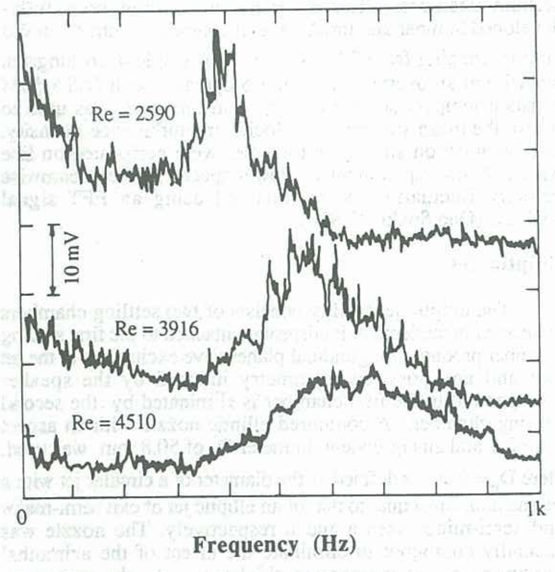

Figure 2 u' spectra at (15D,0.3D) for 3.18mm tube.

The preferred mode for a tube jet is expressed as a Strouhal number St (based on $\bar{U}_e$ and D) which is determined from the preferred frequency for different tube diameters and Reynolds numbers. As shown in Figure 3, St increases with Re and appears to approach an asymptotic value of 0.5.

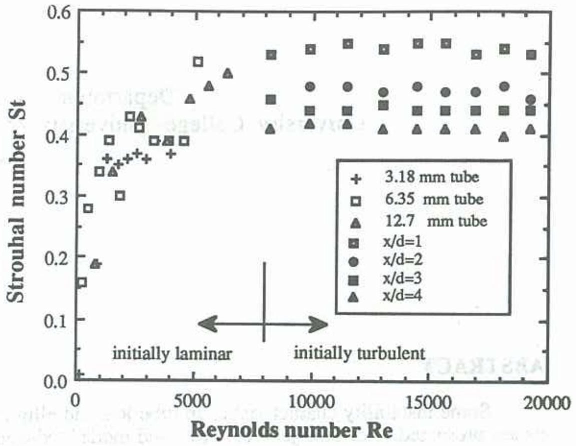

Figure 3 Variation of St with Re.

Fully-developed turbulent exit condition. The mean velocity profiles at 0.25D from the exit of an 12.7mm tube are plotted in Figure 4 for various Reynolds numbers, showing reasonable agreement with the 1/7th power law profile.

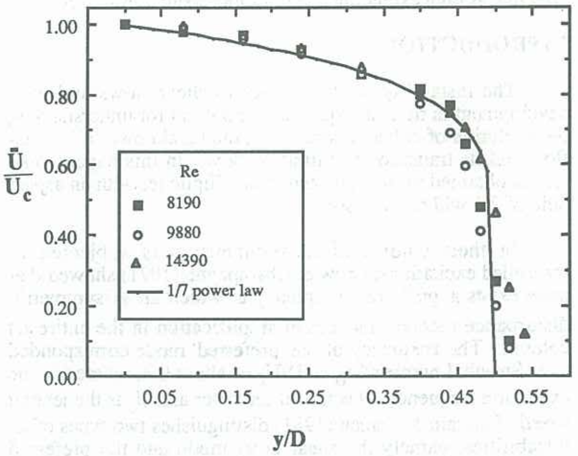

Figure 4 Mean velocity profiles at 0.25D from jet exit.

Typical power spectra of u' at the centre-line are shown in Figure 5 for Re= 19210 and various streamwise distances x/D. Contrary to laminar exit conditions, the preferred frequency of the spectral hump for a fully-developed turbulent exit condition is dependent on the radial location. The preferred frequencies, expressed as St, for various Re and x/D have been determined from the mean frequencies of the spectral humps at the centre-line of the jet and are plotted in Figure 3 for comparisons with laminar exit conditions. It can be seen from Figure 3 that at a given x/D, St is independent of Re. If the preferred mode is determined at the end of the turbulent core where the centre-line velocity is 95% of the exit velocity (and in this case, at x/D=4), St attains a value of about 0.4, which is consistent with results reported in literature (for example, Hussain & Zaman (1981)).

Elliptic Jet

The exit streamwise velocity fluctuation for the unexcited jet is less than 0.1% of the exit velocity. The exit momentum thickness of the shear layers in both the minor-axis and major-axis planes has been measured agrees with each other to within 5%. The shape factor for various Re is about 2.6.

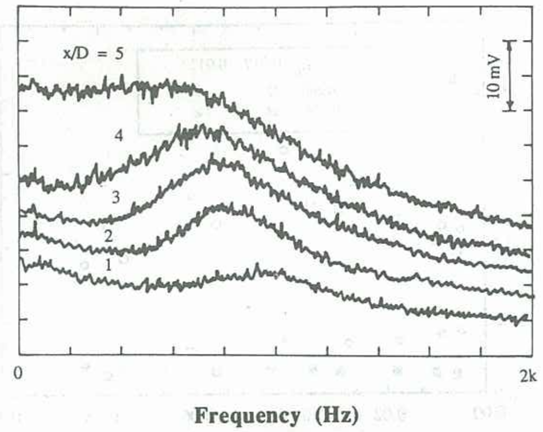

Figure 5 u' spectra at centre-line of jet for Re= 19210.

Turbulence suppression in the minor-axis and major-axis planes. Based on the studies of Zaman & Hussain (1981), maximum turbulence suppression for circular and plane jets occurs at around $St_\theta = 0.17$. 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% measured at the jet exit centre-line. 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.

Figure 6 shows the profile of u'_{ex}/u'_{un} in the minor-axis plane at $x/D_e=1$. 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 0.5f while large scale structures with a frequency of 0.25f appear to be dominant for $St_\theta = 0.017$. The streamwise fluctuation levels for both excitation conditions are higher than those for the unexcited jet.

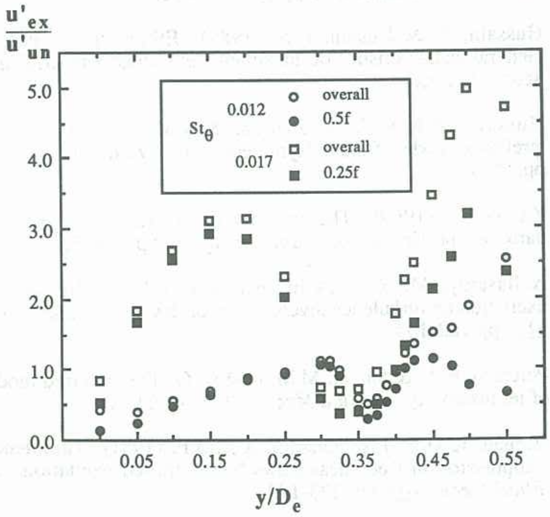

Figure 6 Normalised streamwise velocity fluctuation levels in the minor-axis plane at $x/D_e=1$.

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 7. In fact, turbulence suppression (expressed as u'_{ex}/u'_{un}) has been achieved over 90% of the jet.

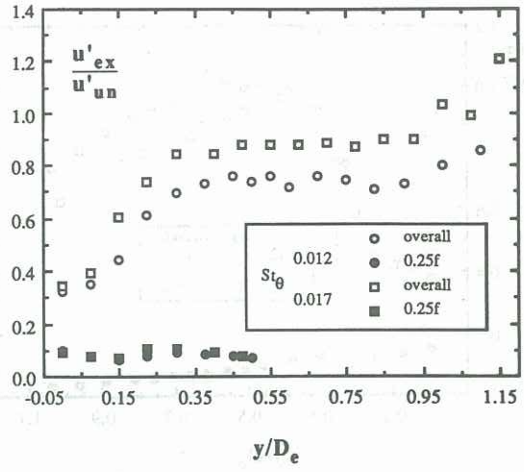

Figure 7 Normalised streamwise velocity fluctuation levels in the minor-axis plane at $x/D_e=4$.

The streamwise velocity fluctuation profile for the excited jet has been normalised by that for the unexcited jet and has been plotted in Figures 8 and 9 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 6 and 7. 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% of the jet by $x/D_e=4$.

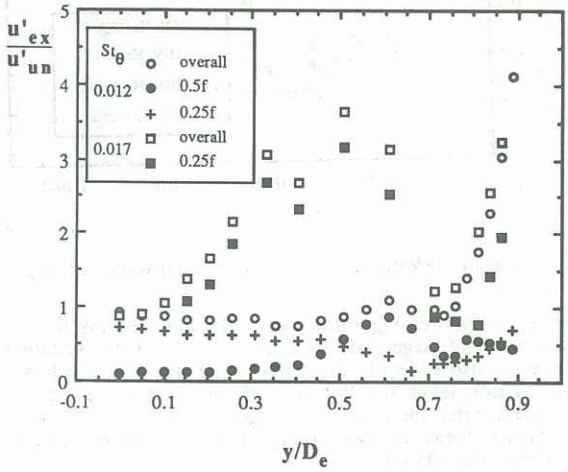

Figure 8 Normalised streamwise velocity fluctuation levels in the major-axis plane at $x/D_e=1$.

Effect of St on turbulence suppression. The turbulence intensity at the centre-line for $x/D_e= 4$ has been measured for the unexcited jet (u'_{un}) and for the excited jet (u'_{ex}) at 620 Hz and 1050 Hz with excitation levels (u'_f/U_e) of 0.5% and 1% measured at the jet exit centre-line. The variation of turbulence suppression (u'_{ex}/u'_{un}) with Strouhal number St_θ (based on exit momentum thickness) is plotted in Figure 10. It can be seen from Figure 10 that for the excitation levels tested, turbulence suppression of the order of 50% has been achieved for $0.08 \le St_\theta \le 0.022$.

Effect of excitation level on turbulence suppression. The variation of turbulence suppression at the centre-line of the jet for $x/D_e = 4$ is plotted in Figure 11 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%) is just as effective as high excitation

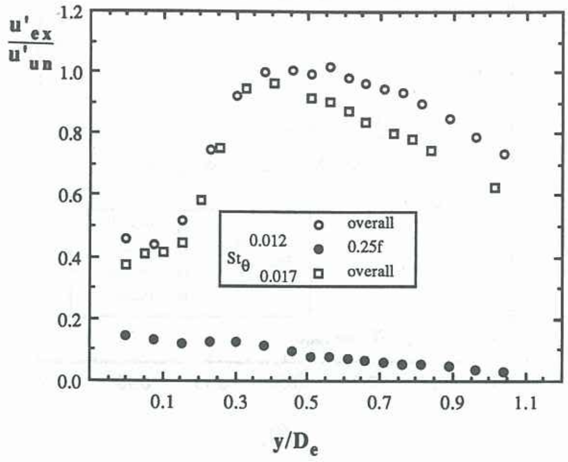

Figure 9 Normalised streamwise velocity fluctuation levels in the major-axis plane at x/D_e=4.

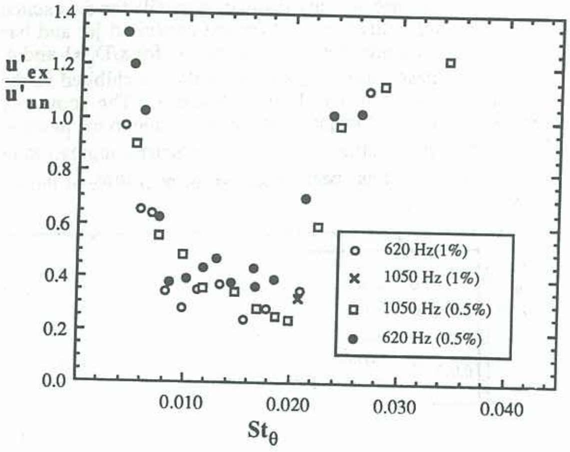

Figure 10 Variation of turbulence suppression with St_θ.

level in suppressing turbulence. This is perhaps due to saturation of large-scale structures at the higher excitation levels. Also shown in Figure 11 is the streamwise velocity fluctuation level at 0.25f (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

The preferred mode of a tube jet has been determined in terms of Strouhal number St (based on average jet exit velocity and tube diameter). For fully-developed laminar exit conditions, St increases with Reynolds number Re and appears to approach an asymptotic value of 0.5 while for fully-developed turbulent exit conditions, St is independent of Re and attains a value of about 0.4.

Turbulence suppression has been observed in an elliptic jet with an aspect ratio of 2:1 for $0.005 \leq St_\theta \leq 0.024$. Small amplitude (0.5%) of excitation is as effective as large amplitude

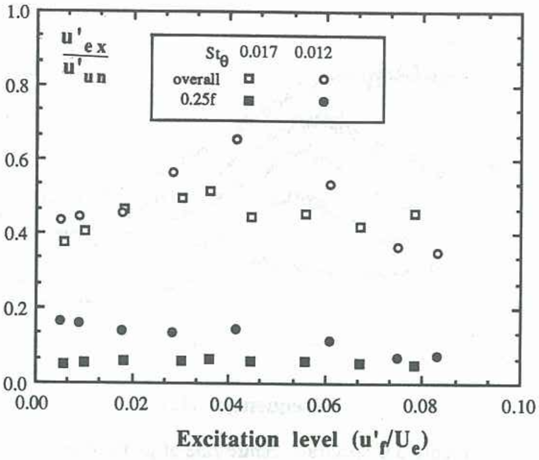

Figure 11 Variation of turbulence suppression with excitation level.

of excitation (8%) in suppressing turbulence perhaps due to saturation of large-scale vortex structures.

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