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DEVELOPMENT OF THE MIXING LAYER OF A PLANE JET UNDER ACOUSTIC EXCITATION

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ABSTRACT

The development of the mixing layer of a plane jet of aspect ratio 6.7:1 subjected to harmonic acoustic excitation was investigated by making measurements of mean velocity, turbulent velocity fluctuations and Reynolds shear stresses at a Reynolds number R_D ($\equiv U_0 D/\nu$, where U_0 is the jet exit velocity, D is the jet nozzle width and ν is the kinematic viscosity) of 3.3×10^4. Excitation of the jet was achieved by using a speaker placed near the exit plane of the nozzle. At several discrete excitatin frequencies the growth rate of the mixing layer showed an increase but the maximum growth rate was observed at a Strouhal number St_D ($\equiv fD/U_0$, where f is the excitation frequency) of 0.34. The mean velocity distribution of the excited layer exhibited good similarity but the velocity fluctuations and Reynolds shear stresses did not exhibit such a good similarity. The influence of excitation is large near the nozzle exit plane and tends to decrease downstream.

INTRODUCTION

The use of periodic excitation for the control as well as understanding of turbulent flows is gaining widespread attention. It is now well established that at discrete excitation frequencies, the growth, entrainment and mixing in a jet can be enhanced (e.g. Thomas and Goldschmidt, 1986; Hussain and Thompson, 1980) whereas suppression of turbulence can be achieved at higher excitation frequencies (Zaman and Hussain, 1981). Excitation can be used to reduce the randomness in phase, size and occurrence of the large scale, organised structures which seem to play an important role in the development of a mixing layer. A general review of the excited shear layers is given by Ho and Huerre (1984) and of the organised structures by Wygnanski and Petersen (1987).

Acoustic speakers and horns driven by a sine wave are the most frequently used devices for excitation. There are several discrete excitation frequencies which have a significant impact on the flow development. When the excitation frequency corresponds to the instability frequency of the initial shear layer ($St_\theta \equiv f\theta/U_0 = 0.017$, where θ is the momentum thickness of the boundary layer at the nozzle exit plane), maximum suppression of turbulence occurs (Zaman and Hussain, 1981). On the other hand, when the excitation Strouhal number St_D is in the range of 0.25 to 1, an increase in entrainment, mixing and growth of the shear layer is observed; however, the maximum growth corresponds to $St_D \simeq 0.3$, called the "preferred mode" (Crow and Champagne, 1971). Chambers and Goldschmidt (1983) obtained an increase in growth of 22% and 9% respectively at $St_D = 0.3$ and 0.65 for an excited jet compared to an unexcited case. Disimile (1986) observed that the vortex structure was more organised in the near field of a two-dimensional mixing layer under a weak excitation. It has also been observed that the influence of excitation decreases after some downstream distance (e.g. Disimile; Zaman and Hussain; Ho et al., 1992).

In general, the mixing layer zone of a plane and circular jet has not been investigated in as much detail as the fully developed jet under excitation. The main aim of the present work is to study the influence of a harmonic excitation on the development of the mixing layer of a plane jet by making measurements of mean velocity, turbulent velocity fluctuations and Reynolds shear stress and to investigate whether normalised mean velocity and turbulent velocity fluctuations exhibit a universal distribution.

EXPERIMENTAL CONDITIONS

The experiments were conducted in an open jet unit consisting of a variable speed fan supplying air to a diffuser followed by a 340 mm × 340 mm settling chamber and a 51 mm × 340 mm nozzle. The experiments were conducted at a jet exit velocity of 9.8 m/s which corresponds to a Reynolds number $Re_D = 3.3 \times 10^4$. The boundary layer at the nozzle exit plane was not tripped and the mean velocity distribution showed a reasonable agreement with a Blasius profile. The momentum thickness Reynolds number Re_θ ($\equiv U_0\theta/\nu$) was 140. The exit free stream turbulence level was 0.8%. Periodic acoustic forcing was achieved by feeding a sine wave through a power amplifier to a 100 W speaker mounted near the exit plane of the nozzle. Mean velocity and turbulent velocity fluctuations were measured using hot wire probes made of 5 μm diameter Pt-10% Rh wires. Measurements were made over a range $1 \leq x/D \leq 5$ where x is the longitudinal distance measured from the nozzle exit plane.

RESULTS AND DISCUSSION

Unexcited Flow

Before making measurements in the excited mixing layer, flow characteristics of the unexcited layer were obtained to ensure that mean velocity and turbulent velocity fluctuations exhibited similarity and to provide a basis for comparison with the excited flow.

Mean Velocity Distribution. Mean velocity distributions were obtained at five longitudinal distances $1 \leq x/D \leq 5$ and the growth of the mixing layer is shown in Figure 1. (The growth of the excited layer, to be discussed later, is also plotted in this figure). The straight lines represent the loci of the lateral (y) positions from the tip of the nozzle where $U/U_0 = 0.95$, 0.5 and 0.1. The growth of the layer is linear and the location of the virtual origin x_0 is at the nozzle exit plane — i.e. $x_0 = 0$. The slope of the $U/U_0 = 0.5$ line is 0.038 and the ratio $(y_{.95} - y_{.1}/x - x_s)$ is 0.2. These results are in good agreement with the results of other investigations in an untripped mixing layer (see, for example, Rajagopalan and Antonia, 1980). The mean velocity U/U_0 plotted against η $(\equiv y/(x - x_0)$ shows good similarity for $2 \leq x/D \leq 5$ (Figure 2a).

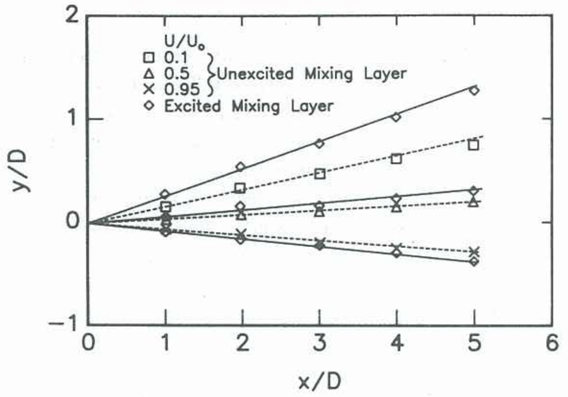

Figure 1 Growth of unexcited and excited mixing layer.

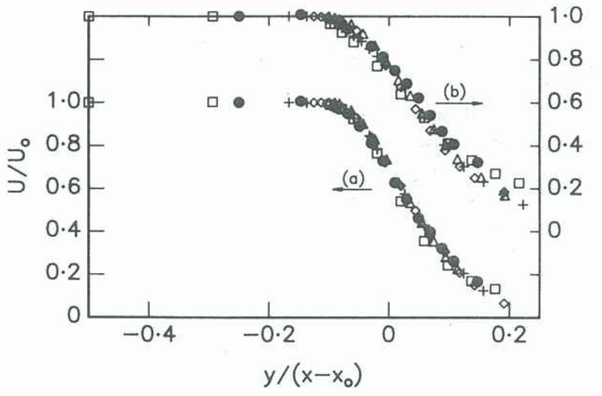

Figure 2 Normalised mean velocity distribution. (a) Unexcited flow; (b) Excited flow. □, $x/D = 1$; ●, $x/D = 2$; +, $x/D = 3$; ◇, $x/D = 4$; △, $x/D = 5$.

Turbulent Fluctuations. The distributions of normalised rms longitudinal and lateral velocity fluctuations (u' and v', where a prime denotes rms value) are shown in Figures 3a,4a. The u' profile exhibits good similarity throughout the layer whereas v' shows a reasonable similarity distribution only for $x/D \geq 3$. The distribution of Reynolds shear stress $\overline{uv}$ normalised by jet exit velocity U_o can also be seen to have a reasonable similarity (Figure 5a).

Before conducting detailed experiments with excitation, the instability frequency of the shear layer was obtained from the spectrum of the signal from a single hot wire placed close to the nozzle exit plane. The dominant frequency or "roll-up" frequency corresponds to $St_\theta = 0.012$, a value obtained by several investigators (e.g. Zaman and Hussain).

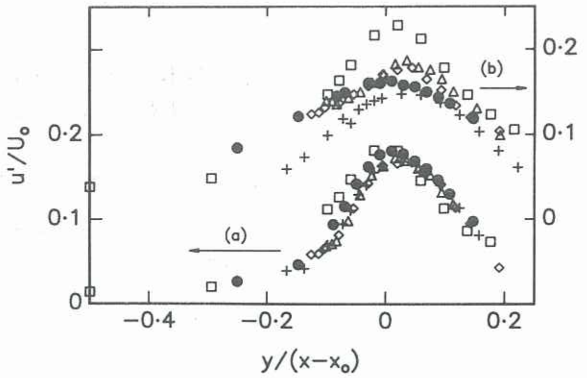

Figure 3 Normalised rms longitudinal velocity fluctuation (u') distribution. (a) Unexcited flow; (b) Excited flow. Symbols are as in Figure 2.

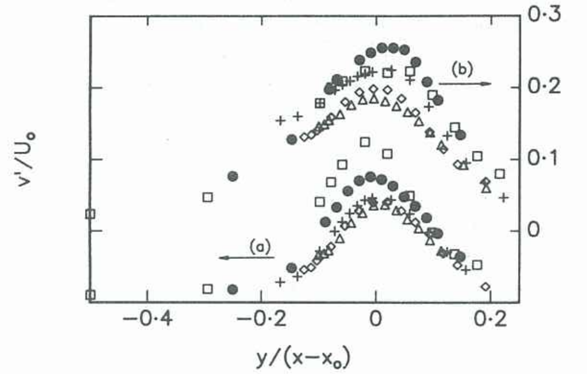

Figure 4 Normalised rms longitudinal velocity fluctuation (v') distribution. (a) Unexcited flow; (b) Excited flow. Symbols are as in Figure 2.

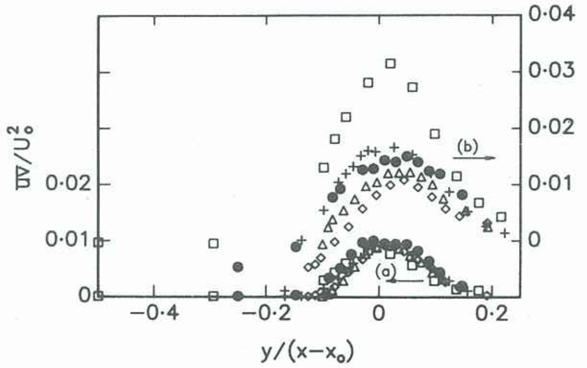

Figure 5 Normalised Reynolds shear stress ($\overline{uv}$) distribution. (a) Unexcited flow; (b) Excited flow. Symbols are as in Figure 2.

Excited Flow

In a plane jet, Thomas and Goldschmidt (1986) used different excitation frequencies to study the influence of Strouhal number on the width of the jet. In the present work, a similar experiment was conducted by feeding a constant amplitude sine wave over a range of Strouhal number $0 \leq St_D \leq 1.2$. A single hot wire, placed at the location where $U/U_0 = 0.25$ at $x/D = 3$ was used to indicate the width of the layer based on earlier investigations which have shown that the influence of excitation is larger on the low velocity side than on the high velocity side. The plot of the value of y where $U/U_0 = 0.25$ against St_D (Figure 6) shows that there are several discrete frequencies at which the width of the mixing layer exhibits an increase, but the maximum width occurs for an excitation Strouhal number of 0.34 (frequency of excitation = 66 Hz). At this excitation frequency the width of the layer is 48% more than the width of the unexcited layer. It should be noted that the present value of $St_D = 0.34$ is close to the value of 0.3, identified as the "preferred mode" for the maximum growth of the layer. All subsequent measurements for the excited mixing layer were made at a value of $St_D = 0.34$.

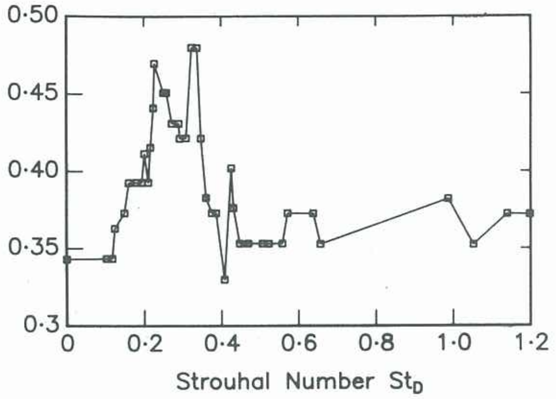

Figure 6 Influence of Strouhal number on widening rate.

Mean Velocity Distribution. The growth of the mixing layer, based on the loci of y locations where $U/U_o = 0.1$, 0.5 and 0.95, is also shown in Figure 1. It can be noted that the growth is linear with the virtual origin x_0 at $x = 0$, but the slopes of the loci are larger than the slopes for the unexcited flow. For example, the slope of the line $U/U_0 = 0.5$ of the excited layer is 37% larger than the unexcited case; the ratio $(y_{.95} - y_{.1}/x - x_0)$ has increased from 0.2 for the unexcited case to 0.32 for the excited case. As a result of the increase in width, the longitudinal extent of the potential core is reduced. The normalised mean velocity distribution also exhibits good similarity for $1 < x/D \leq 5$ (Figure 2b) where the average of the distributions for the unexcited case is also shown for comparison. An increase in the width of the excited mixing layer can also be seen. It has been observed that even a weak forcing at an appropriate frequency enhances the characteristics of the vortical structure in the initial part of the layer and results in an increased growth.

Turbulent Fluctuations. Excitation appears to increase the magnitude of turbulent fluctuations. At $x/D = 1$, u'/U_0 for the excited layer is always larger than u'/U_0 for the unexcited layer. On the high speed side and in the potential core u'/U_0 is consistently larger for the excited case whereas on the low speed side the difference in u'/U_0 between the excited and unexcited flows decreases as x/D increases. Unlike u'/U_0, v'/U_0, is always larger for the excited layer. The axis of the speaker used for excitation is normal to the (x, z) plane and hence the excitation is likely to have a maximum influence on the lateral velocity fluctuations compared to the longitudinal velocity fluctuations. The Reynolds shear stress $\overline{uv}/U_0^2$ is also larger for the excited layer, but the difference decreases as x/D increases. The normalised distributions of u', v' and $\overline{uv}$ (Figures 3b,4b,5b) do not exhibit good similarity like the unexcited flow, but u'/U_0 distributions fall within a narrow band for $x/D > 2$. The large increase in u' and v' near the nozzle exit plane is probably due to the enhancement of the vortical structure under excitation.

CONCLUSIONS

Measurements of mean velocity,. turbulent velocity fluctuations and Reynolds shear stress were made in the mixing layer of a plane jet without and with acoustic excitation. The width of the layer increases appreciably under excitation at a Strouhal number $St_D = 0.34$, which corresponds to the "preferred mode" of the layer. Mean velocity profiles in the excited layer indicate good similarity. The magnitude of turbulent fluctuations u' and v' and the Reynolds shear stress $\overline{uv}$ show significant increase in the excited layer compared to the unexcited layer. The difference in these values between excited and unexcited flows decreases as x/D increases, suggesting that the excited layer slowly relaxes to the unexcited flow. Distributions of u', v' and $\overline{uv}$ in the excited flow do not show good similarity compared to the unexcited flow.

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