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SOME FLOW CHARACTERISTICS OF MECHANICALLY-EXCITED PLANE TURBULENT FREE JETS

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SUMMARY Two methods of mechanically exciting a plane turbulent free jet are described, namely (a) periodic perturbation of the nozzle exit velocity and (b) forced oscillation of a small vane located in the jet potential core. For the periodically-pulsed jet, hot wire measurements indicate that the mean centre-line velocity decay and the mean spreading of the jet do not differ from that of the steady jet. However, unsteady effects are observed in the instantaneous flow quantities; in particular, the peak-to-peak amplitude of oscillation of the instantaneous centre-line velocity varies considerably from the initial value at the nozzle exit and is strongly dependent on frequency. Numerical solution of the thin shear layer equations using Keller 'box method' and a constant eddy viscosity model produces mean flow results which agree with measurements but fail to predict unsteady effects observed experimentally.

Laser Doppler anemometer and pitot tube measurements of the vane-excited jet show a significant increase in entrainment over the steady jet value with increasing amplitude of vane oscillation. Mean centre-line velocity is found to decay more rapidly and is accompanied by a faster jet spreading.

1 INTRODUCTION

Turbulent jets with intentionally introduced unsteadiness are receiving considerable attention for two reasons. Firstly, such excitation of jets provides a means of studying the basic mechanism behind phenomena, such as entrainment, through conditional sampling techniques. Secondly, it offers potential for enhanced entrainment and mixing in practical situations such as fluidics, combustion and aeronautics. Several excitation techniques have resulted in enhanced mixing and entrainment, for example, acoustic excitation (Fiedler & Korschelt (1979)), fluidic excitation (Piatt & Viets (1979)), and mechanically pulsed jets (Bremhorst & Harch (1979)). The present investigation stems from a motivation to provide a simple but efficient method to increase jet entrainment for potential use in thrust augmenting ejectors for VSTOL aircrafts. In this paper, two methods of mechanically exciting a plane turbulent free jet are described, namely, (a) periodically pulsed jet and (b) vane-excited jet. The measuring techniques and some mean flow characteristics of the two excited jets are presented. Numerical modelling has been attempted to predict the instantaneous flow field of the pulsating jet.

2 EXPERIMENTAL SET-UP AND MEASURING TECHNIQUES

2.1 Periodically-Pulsed Jet

Measurements in both a steady and unsteady jet were made in the jet facility shown schematically in Fig. 1. In the unsteady jet, excitation was introduced in the streamwise (x) direction by periodic perturbation of the nozzle exit velocity. This was achieved by venting air from the plenum chamber through an orifice, the area of which was varied sinusoidally by a sliding valve driven by an electromagnetic vibrator. The nozzle, with a width (h) of 5 mm, has an aspect ratio of 60.

Instantaneous velocity measurements across the jet and up to 80 nozzle widths downstream were obtained with a constant temperature hot-wire anemometer. The single platinum alloy hot wire, 10 μm in diameter by 3 mm long, was operated at a resistance ratio of 1.3 and aligned parallel to the length of the nozzle. The linearized hot-wire anemometer output was recorded on FM tapes and subsequently analyzed on an EAI600 hybrid computing system using phase-averaging techniques as described by Lai & Simmons (1980).

The mean jet exit Reynolds number was 1.1×10^4. Pulsation frequencies (f) of 1, 10 and 20 Hz with a peak-to-peak amplitude of pulsation of the nozzle exit velocity on the centreline of 21.4% of the mean nozzle exit velocity $(\overline{U}_{ci})$ were used.

2.2 Vane-Excited Jet

In this jet facility (Fig. 2), an excitation was introduced in the transverse (y) direction by oscillating a vane in pitch about an axis 3 mm aft of its leading edge. The vane which had a symmetric airfoil section with a thickness of 1.3mm, a span of 360 mm and a chord of 10 mm was located symmetrically in the potential core of the jet at 1.42h from the nozzle. The vane was oscillated by a slider-crank mechanism with an eccentricity driven by a motor. Various frequencies

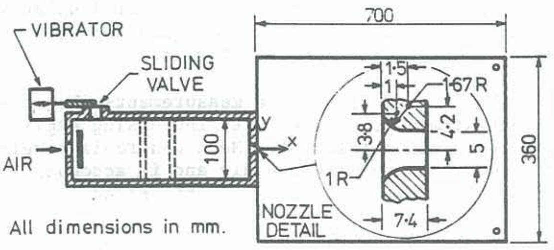

Figure 1 Schematic of Pulsed Jet Facility

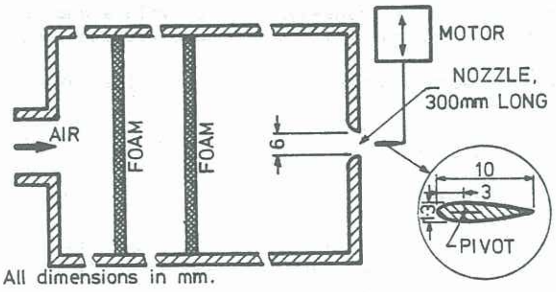

Figure 2 Schematic of Vane excited Jet Facility.

and amplitudes of oscillation of the vane about a mean position set at zero angle of attack could be attained by varying the power input to the motor and the eccentricity.

Earlier measurements obtained with single hot wire by Simmons et al (1981) indicated significant increase in entrainment without loss in nozzle efficiency at a low nozzle pressure ratio (P_C/P_A) of 1.008. Here P_C is the absolute plenum chamber pressure and P_A is the atmospheric pressure. The single hot wire results suffered from the drawback of overestimating the entrainment because the velocity magnitude rather than the mean streamwise velocity component ($\overline{U}$) was measured.

The effectiveness of this type of excitation to provide entrainment increase at a higher nozzle pressure ratio of 1.137 was explored with a laser Doppler anemometer (LDA). To prevent the vane from fluttering at this high nozzle pressure, it was held in four bearings, one at each end and two at midspan separated 123 mm apart. This gave an effective nozzle's aspect ratio of 1:20, still being considered acceptable for plane jets in the literature. Mean velocity measurements were made across the width of the jet at its midspan and at distances of 20, 40 and 60 nozzle widths downstream of the nozzle for the following range of parameters:

Vane frequency of oscillation (f) : 0, 20, 30, 40 Hz.
Vane amplitude of oscillation (ε) : 2.6°, 4.6°, 6.9° (zero peak)

The mean jet exit Reynolds number was 5.8 x 10^4.

In this study, a single component, dual beam LDA was used in the forward scatter mode with an on-axis photomultiplier. The laser was a Spectra-Physics Model 164 Argon-Ion laser operated at a wavelength of 514.5 nm with 500 mW of power. The optics system was a DISA 55L88 transducer with a 600 mm lens. No frequency shifting was employed due to unavailability of hardware. A beam separation of 40 mm was used in traversing the high velocity region while a beam separation of 80 mm was used in the low velocity region to optimize the sensitivity of the LDA. Particles of size less than 1 μm were generated from olive oil by a TSI Model 3075 atomizer and were seeded at a rate of 0.3 cc/min in the plenum chamber. The surrounding environment of the jet was also heavily seeded to ensure a uniform distribution of particles both in the fluid originating from the nozzle and the surrounding so as to eliminate bias due to non-uniform seeding. The Doppler signals detected by the photomultiplier were processed by a DISA 55L90 LDA counter. They were first band-pass filtered to remove the high frequency noise and the low frequency pedestal. The filters were used in conjunction with threshold window adjustments which set the upper amplitude limit to reject signals from large particles and amplifier gain control which attenuated the noise signal to below the circuit trigger level. The signals were then validated on a 5/8 comparison mode with a tolerance accuracy of ± 1.5%. The validated signals were further reduced on-line by an HP 9825A microcomputer to extract the mean streamwise velocity component ($\overline{U}$) using a one-dimensional weighting algorithm due to McLaughlin & Tiederman (1973) to correct for statistical bias. On-line histogram plots of particle velocity distribution were used to help select the most appropriate band-pass filter values and to discriminate against filter resonance frequencies.

Results were compared with those obtained by a Pitot-static tube.

3 RESULTS

3.1 Periodically-Pulsed Jet

Measurements in the steady jet indicate that the centre-line velocity decay rate, the spreading rate and entrainment all fall within the ranges of values reported in the literature. For the unsteady jet at all the frequencies tested, the mean flow characteristics such as the mean velocity profiles, the centre-line velocity decay rate and jet spreading rate follow those of the steady jet. Consequently, the mean entrainment $(Q(x) - Q_E)/Q_E$ differs insignificantly from that for the steady jet. Here Q(x) is the mean volume flow rate at each x location, obtained by integrating the velocity profile and Q_E is the mean volume flow rate at the exit.

Unsteady effects, however, are observed in the instantaneous characteristics. In particular, the peak-to-peak amplitude of oscillation of the instantaneous centre-line velocity, expressed as a percentage F of the local mean centre-line velocity, varies considerably from its initial value at the nozzle exit (Fig. 3). For frequencies of 1 Hz and 10 Hz, F peaks at about x/h = 10 (within the transition region) and decays until x/h = 40. For the 20 Hz case, F peaks at about x/h = 40 after which it drops drastically to below its initial value. The trend indicates that perhaps unsteady effects due to pulsation only dominate the first 50 nozzle widths, where self-preservation still has not been attained, and decay at large streamwise distance.

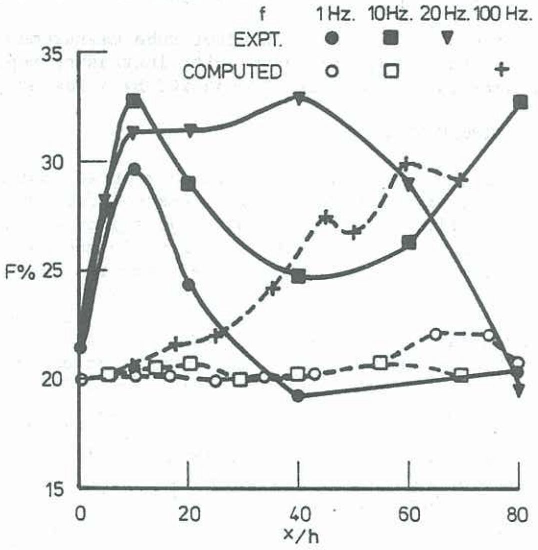

Figure 3 Variation of F with x/h

3.2 Vane-excited Jet

The steady jet profile measured by LDA agrees very well with the Pitot-static tube results (Fig. 4). However, in the unsteady jet, the Pitot-tube results are higher than those of the LDA in the main jet stream because the Pitot-tube response consists mainly of $(\overline{U}^2 + \overline{u^2})^{\frac{1}{2}}$ whereas the LDA only measures $\overline{U}$. Here u is the fluctuation in the streamwise direction.

Although there are some discrepancies between the LDA and Pitot-tube results, they both indicate a significant increase in entrainment over the steady jet value (Fig. 5). The LDA results do not display a definite trend of increase in entrainment with frequency as the Pitot tube results do.

Both the LDA and Pitot-tube measurements show that the jet entrainment increases with increasing amplitude of vane oscillation (Fig. 6). Mean centre-line velocity is found to decay more rapidly and is accompanied by a faster jet spreading than for the steady jet.

4 NUMERICAL MODELLING OF A PERIODICALLY PULSED JET

4.1 Problem Formulation

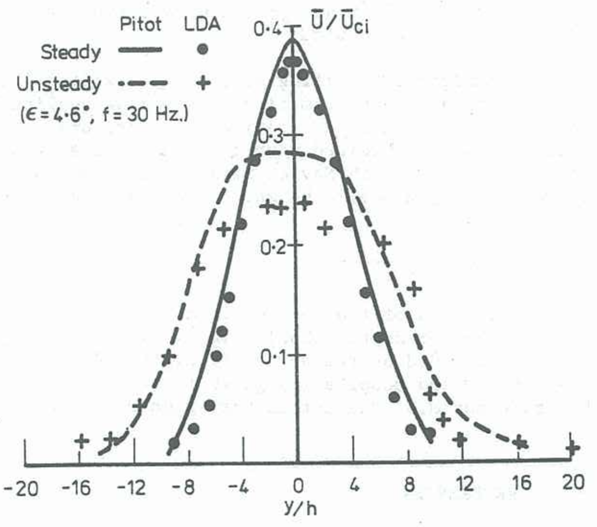

Figure 4 Comparison between LDA and Pitot-tube measurement for steady and vane-excited jet at x/h=40

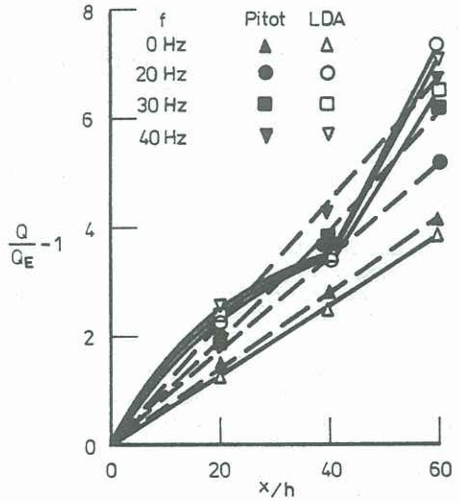

Figure 5 Variation of entrainment with streamwise distance for ε = 4.6°.

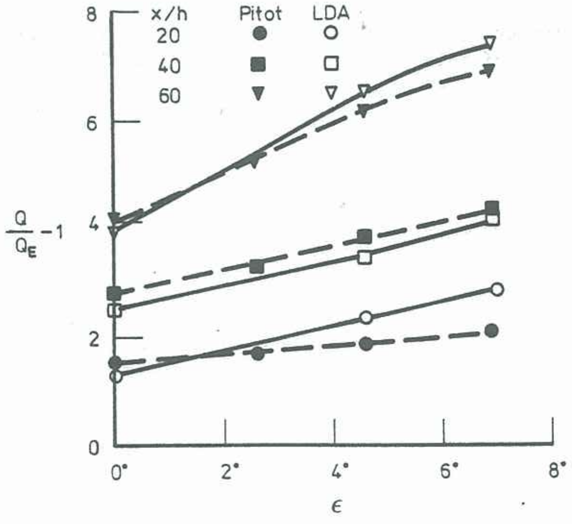

Figure 6 Variation of entrainment with vane amplitude of oscillation for 30 Hz.

By using Reynolds decomposition, thin shear layer approximations and time-averaging in the Navier Stokes and the continuity equations, the following non-dimensional governing equations of a periodically pulsed jet are obtained.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{\partial}{\partial y}\left(\nu\frac{\partial u}{\partial y} - \overline{u'v'}\right) \qquad (1)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (2)$$

Here u and v are the non-dimensional ensemble-mean velocities in the x and y directions with the corresponding fluctuations u' and v', and ν is the non-dimensional kinematic viscosity. The velocity and length scales used for non-dimensionalisation are $\overline{U}_{ci}$ and h respectively. The boundary and initial conditions are given by

$$t \geqslant 0 \begin{cases} y = 0 & \frac{\partial u}{\partial y} = v = 0 \\ y = \infty & u = 0 \\ x = 0 & u = u_o(y)(1 + \varepsilon \sin 2\pi ft) \end{cases} \qquad (3)$$

$$t = 0 \qquad x \geqslant 0 \qquad u = u_i(x,y) \qquad (4)$$

where u_i is the initially steady velocity field.

A Prandtl type constant eddy viscosity ν_t is assumed for the turbulence model so that

$$\overline{u'v'} = -\nu_t\frac{\partial u}{\partial y} \qquad (5)$$

$$\nu_t(t) = cy_{\frac{1}{2}}u_c(t) \qquad (6)$$

where c is a constant, $y_{\frac{1}{2}}$ is the jet half-width and u_c is the centre-line velocity.

Lai & Simmons (1981) show that a transformation based on the similarity solution for a steady jet reduces substantially the mean rate of spreading of an unsteady laminar jet in a computational grid, thereby enabling the use of variable grids over predetermined regions to achieve efficient computation. Here a similar transformation is used so that a dimensionless transverse distance η and stream function f are defined by (7) and (8).

$$\eta = ay(x + x_o) \qquad (7)$$

$$\psi(x,y,t) = b(x + x_o)^{\frac{1}{2}} f(x,\eta,t) \qquad (8)$$

where ψ is the dimensionless stream function in (x,y,t) coordinates and a, b and x_o are arbitrary constants chosen to facilitate computation.

The function f automatically satisfies (2) and (1) can be transformed to (9)

$$(x + x_o)^{\frac{1}{2}}(\nu_{eff} f'')' + (f')^2 + ff'' = 2(x + x_o)\left[f'\frac{\partial f'}{\partial x} - f''\frac{\partial f}{\partial x} + \frac{(x + x_o)^{\frac{1}{2}}}{ab}\frac{\partial f'}{\partial t}\right] \qquad (9)$$

where prime denotes ∂/∂η

$$\nu_{eff} = \nu_t + \nu$$

$$\nu_t = cb(x + x_o)^{\frac{1}{2}}\eta_{\frac{1}{2}} f'_c(t) \qquad (10)$$

The boundary and initial conditions become

$$t \geqslant 0 \begin{cases} \eta = 0 & f'' = 0 \quad f + 2(x + x_o)\frac{\partial f}{\partial x} = 0 \\ \eta = \infty & f' = 0 \\ x = 0 & f' = f'_o(\eta)(1 + \varepsilon \sin 2\pi f\, t) \end{cases} \qquad (11)$$

$$t = 0 \qquad x \geqslant 0 \qquad f' = f'_i(x,\eta) \qquad (12)$$

Equation (9) is parabolic and can be solved by a marching procedure. The finite difference scheme employed was the Keller 'box method' (Cebeci & Bradshaw (1977)). The constant c in (10) was chosen to match the steady jet solution with available measurements. Consequently, for all x and y,

$$c = \begin{cases} 0.009 \text{ for } \overline{u}_c \geqslant 0.95 \\ 0.034 \text{ for } \overline{u}_c < 0.95 \end{cases}$$

where $\overline{u}_c$ is the mean centre-line velocity.

The constants a, b and x_o were given values of 0.3, 0.6 and 3.75 respectively.

The mean velocity profile at the nozzle ($u_o(y)$) was chosen to match experimental 'top-hat' profile. Details of the solution procedure are available in Lai & Simmons (1980).

4.2 Results

The numerical results for the mean flow characteristics of the periodically pulsed jet agree very well with the experiments. Unsteady effects in the instantaneous characteristics are observed. However the computed F for 1 and 10 Hz is almost independent of the streamwise distance as opposed to the experimental results (Fig. 3). The phase angle of the steady-state fundamental component of the centre-line velocity at any streamwise station relative to that at the nozzle exit is a lag which increases with both frequency and streamwise distance. This trend predicted by the model agrees with the experimental observation but the quantitative agreement is not satisfactory.

5 CONCLUSIONS

The non-dimensional frequency of excitation ($fh/\overline{U}_{ci}$) in the vane-excited jet ranges from 0.008 to 0.0016 compared with 0.0001 to 0.0028 for the periodically pulsed jet. Although this is a very low frequency range, results indicate that the vane-excited jet produces a significant increase in entrainment over the steady jet value even at a high nozzle pressure ratio of 1.137 compared with no increase for the pulsed jet. Hence, an excitation introduced in the transverse direction of a jet is a much more effective means of enhancing mixing and entrainment than a streamwise excitation. More detailed flow measurements are required to establish the role of coherent structures in different types of excitation.

By using a constant eddy viscosity model and thin shear layer approximations, the numerical model predicts very well the mean flow characteristics of the pulsed jet but fails to predict unsteady effects which agree quantitatively with experiments. Only the general trends are predicted. Hence, in order to predict accurately the instantaneous flow field of an unsteady jet, a more refined turbulence model has to be used.

For the numerical modelling of the vane-excited jet, thin-shear layer approximations may not be applicable because of transverse excitation. Comparisons between results obtained with thin shear layer equations and those with Navier Stokes equations for the vane-excited jet should be made. Such a study is now in progress.

6 ACKNOWLEDGEMENTS

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