Technical Notes

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Instantaneous Velocity Measurements in a Periodically Pulsed Plane Turbulent Jet

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Introduction

WITH the recent advances in numerical modeling techniques and computer technology, good predictions can now be obtained for a variety of steady turbulent shear flows. On the other hand, unsteady turbulent shear flows have been computed with almost no complementary experimental guidance,[1] so that there is a need for data to enable evaluation of mathematical models in unsteady situations. The entrainment of surrounding fluid is an important characteristic of free shear flows but the underlying mechanism is still not fully understood.[2] This Note is directed primarily toward extending the available experimental data on a particular unsteady shear flow, the periodically pulsed plane turbulent jet.

The excitation of turbulent jets by acoustic, mechanical, and fluidic means has attracted considerable interest in recent years because of the fundamental and practical implications of an improved understanding of the jet entrainment characteristics. For example, jet thrust augmentation of VSTOL aircraft can be achieved if entrainment can be enhanced. Acoustic excitation studies have been performed by Crow and Champagne,[3] Goldschmidt and Kaiser,[4] and Fiedler and Korschelt.[5] Fluidic excitation has been pioneered by Viets[6] and further investigated by Piatt and Viets.[7] Mechanically pulsed jets with time-varying mass flows have been studied by Binder and Favre-Marinet,[8] Curtet and Girard,[9] and Bremhorst and Harch.[10] A secondary aim of this study is the measurement of the effect of periodic pulsation on the entrainment characteristics of a plane turbulent jet.

Experimental Apparatus and Procedure

Apparatus

Measurements in both a steady and an unsteady jet were performed in the facility shown schematically in Fig. 1. The jet of air issued into stationary air from a rectangular nozzle with length $\ell = 300$ mm and width $h = 5$ mm. The nozzle profile was based upon Brithish Standard BS1042.[11] Air from a compressor was passed through a heat exchanger which was able to keep the jet temperature at the nozzle exit to within 1°C above the ambient air temperature. Foam and wire gauze within the plenum chamber reduced the turbulence intensity at the nozzle exit for the steady jet to about 0.3%. Side plates extending 700 mm downstream of the nozzle were used to enhance the two-dimensionality of the jet so that at 100 nozzle widths downstream of the nozzle the centerline velocity variation over the central 50 mm of the length of the steady jet was less than 2%.

The jet was excited by periodic pulsation of the nozzle exit velocity about the value for the steady jet. 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.

Instrumentation

Instantaneous velocity measurements across the jet and up to 100 nozzle widths downstream of the nozzle 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 an overheat ratio of 1.3 and aligned parallel to the length of the nozzle.

To enable control of the amplitude of the velocity perturbations, the motion of the sliding valve was measured with a displacement transducer. The sinusoidal output of a function generator was used both to drive the electromagnetic vibrator and to provide a reference signal for data analysis. The linearized hot-wire anemometer output and the reference signal were stored with an FM tape recorder. The recording bandwidth was 1250 Hz except for the experiments at 1 Hz pulsation frequency when the bandwidth was reduced to 312 Hz. Subsequent analysis was performed on an EAI 600 hybrid computing system.

Data Analysis

The instantaneous wire cooling velocity vector C is given by

$$\underset{\sim}{C} = (U+u)\,\underset{\sim}{i} + v\,\underset{\sim}{j} \tag{1}$$

in terms of the mean and the fluctuating components U and u in the streamwise x direction and the fluctuation v in the y direction, $\underset{\sim}{i}$ and $\underset{\sim}{j}$ being unit vectors. If both u and v are small compared with U, time-averaging $\underset{\sim}{C}$ yields

$$\bar{C} = U \tag{2}$$

By using the reference signal $A\sin\omega t$ for timing, it was possible to study the velocity field at each of 12 sample times $t = \tau_i$ during one period $T = 2\pi/\omega$ of pulsation, where τ_i is given by

$$\tau_i = (1/12)(i-1)T, \qquad i = 1,2,\ldots,12 \tag{3}$$

The positive-going zero crossings at the start and end of each period of the reference signal were used to define the start and end of an ensemble in the linearized anemometer signal. About 500 successive ensembles were sampled at each τ_i and stored in a normalized histogram with 401 cells to calculate the ensemble-average velocity

$$\tilde{C}(\tau_i, x, y) = E(C) \tag{4}$$

where E is the ensemble expectation operator. If both u and v are small compared with U, the ensemble-average velocity $\tilde{C}$ can be taken equal to $\tilde{U}(\tau_i, x, y)$. Its distribution over y for a given x and τ_i is referred to here as an instantaneous velocity profile. Mean (time-averaged) velocity profiles were obtained by averaging the instantaneous velocity profiles at a given x

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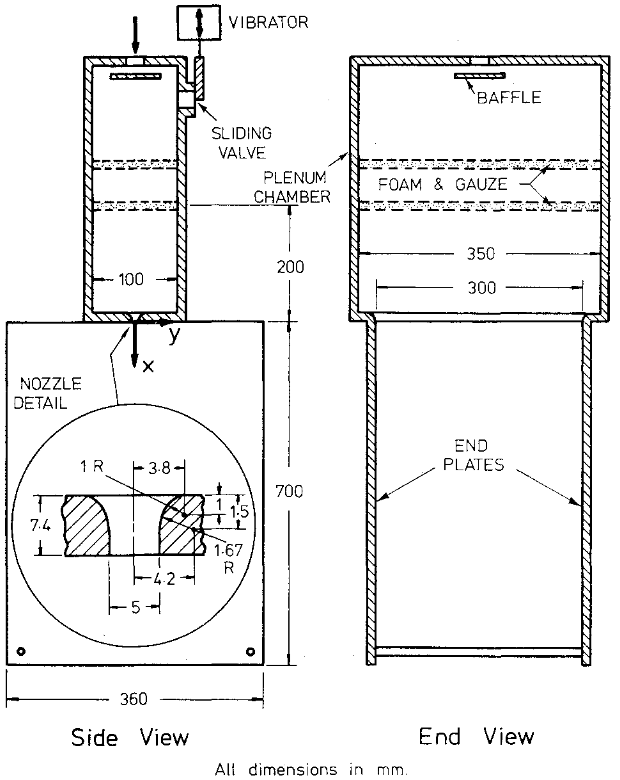

Fig. 1 Schematic of pulsating jet facility.

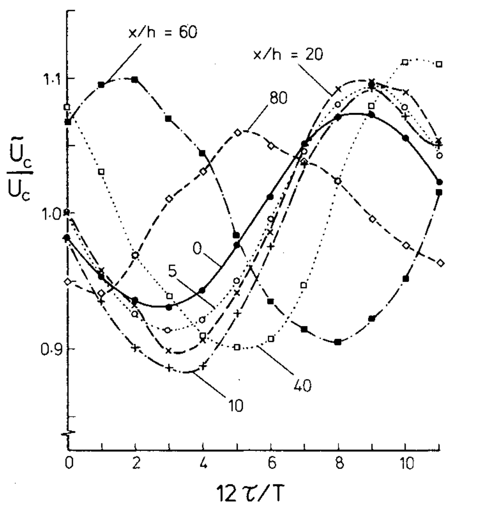

Fig. 2 Variation of centerline velocity with time at 20 Hz.

over all 12 sample times τ_i. Significant measurement error can be expected near the edge of the jet where turbulence intensities are high and v is of the order of U. For this reason emphasis is placed on velocity measurements on the centerline.

Experimental Conditions

The mean jet exit Reynolds number was 1.1×10^4 and instantaneous velocity profiles were obtained up to 80 nozzle widths downstream at pulsation frequencies of 1, 5, 10, and 20 Hz. The peak-to-peak amplitudes of pulsation of the nozzle exit velocity on the centerline, corresponding to these frequencies, were respectively 21.5, 21.3, 21.9, and 14.6% of the mean nozzle exit velocity on the centerline.

Results and Discussion

Measurements in the steady jet indicate that the rate of decay of the centerline velocity, the spreading rate, and the

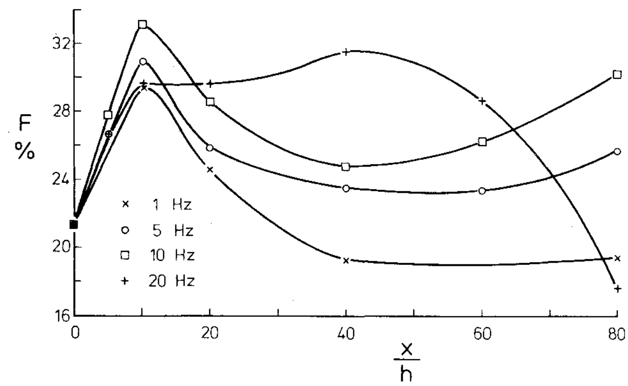

Fig. 3 Amplitude of oscillation of centerline velocity.

momentum conservation all fall within the ranges of values reported in the literature. Hence the steady jet in this study is a good basis for unsteady experiments. Only representative results for the pulsed jet are reported here, the full results being available in Ref. 12. At every streamwise location and for all pulsation frequencies and amplitudes, the mean profiles collapse onto the corresponding steady jet profile. Although there is evidence of slight departure of the shape of some instantaneous profiles from the steady jet profile, this possible unsteady effect is not conclusive enough to provide a test for the evaluation of theoretical predictions.

The decay of the mean centerline velocity and the mean spreading of the pulsed jet are also seen to agree well with the steady jet values, allowing for experimental error. The mean flow rate $Q(x) = \int_{-\infty}^{\infty} U\mathrm{d}y$ at each x location was obtained from the mean velocity profiles using the fairing in a procedure advocated by Crow and Champagne[3] for the tails. As can be expected from the mean decay and spreading results, the mean entrainment $(Q(x) - Q_E)/Q_E$ (where Q_E is the mean flow rate at the nozzle exit) differs insignificantly from that for the steady jet. Recently there has been a growing realization that large coherent vortices play a primary role in the entrainment process.[2] It is likely that the frequencies and amplitudes of pulsation in these experiments are not large enough to promote the formation of large vortices. The above results suggest that for the range of frequency and amplitude of pulsation used, the mean flow behavior can be obtained from a quasisteady turbulent flow model. However, there is a need to conduct experiments at higher frequencies and amplitudes of pulsation to evaluate fully the potential of this type of excitation for enhancement of entrainment; however practical difficulties are likely to arise if the frequency is to be increased significantly with Reynolds number maintained at the value used in these tests.

Results in Fig. 2 typify the variation of the centerline velocity with time. Distortion of the waveforms can be observed and there is always a phase lag, increasing with streamwise distance, between the fundamental component of the centerline velocity at any downstream station and that at the nozzle exit. Similar distortion was predicted by Lai and Simmons[13] in their numerical analysis of a pulsed two-dimensional laminar jet.

The peak-to-peak amplitude of oscillation of the instantaneous centerline velocity, expressed as a percentage F of the local mean centerline velocity, varies considerably from the initial value at the nozzle exit (Fig. 3) and is strongly dependent on frequency. To aid comparison the results have been scaled so that values of F at the nozzle exit for the various frequencies all assume the value for the 1 Hz case. This adjustment is minor except for the 20 Hz case. The variations of F with x/h at various frequencies show similar trends, except for the 20 Hz case. This phenomenon has been predicted by Lai and Simmons[13] for a pulsed laminar jet and is the most significant unsteady effect observed in the experiment.

These measured unsteady effects, in particular the measurements of amplitude of oscillation, provide fundamental data for evaluation of unsteady shear flow models. This work is presently being done by the authors.

Acknowledgment

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Numerical Solutions of Transonic Flows by Parametric Differentiation and Integral Equation Techniques

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Introduction

RECENT experimental and theoretical investigations of external transonic flows over aerodynamic elements have as their goal the prediction of such flows with greater accuracy and efficiency. Tijdeman and Schippers[1] and Davis and Malcolm[2] have provided an excellent set of experimental data to assist in the development of analytical models of transonic flows. The theoretical research programs may be considered chiefly under three classifications: finite-difference approximations,[3] finite-element approximations,[4] and integral equation methods.[5-10] The incentive for using integral equation methods (IEM) over conventional finite-difference approaches lies in the apparent relative easiness in numerically solving the integral equation.

Recent advances in IEM's have resulted in predictions of both lifting and nonlifting cases including supercritical flows. The results obtained by Nixon[10] represent a significant advance in IEM development. In addition to considering first-order corrections for shock wave curvature, Nixon[10] has eliminated the simplification that the perturbation velocity is zero upstream and downstream of the airfoil. Independently, we have developed an IEM which is free of this simplification of the perturbation velocity field.[11]

This paper describes the results of an exploratory study of the advantages obtained by combining IEM's with the method of parametric differentiation.[12] In this particular application of the method of parametric differentiation (MPD), the approach is distinctively different from the approach used by Norstrud.[5] In Norstrud's application of the MPD, the method is exploited to solve a system of nonlinear algebraic equations. Also, Norstrud's formulation retains the disputable assumption that the perturbation velocity is zero upstream and downstream of the airfoil.

In the present method, the nonlinear unsteady transonic flow equation for small perturbations is transformed into a linear equation with the use of the MPD. The linear equation is split into a pair of weakly coupled partial differential equations by writing the transformed perturbation potential as the sum of a steady component and an unsteady component. The solution of the steady equation as an integral equation is based on Ogana's[8] treatment. However, the numerical solution of the integral equation and the handling of the singularity of the integrand are done in an entirely different manner. As a test case, the formulation developed in this paper is applied to predict the steady transonic flow over a nonlifting parabolic-arc airfoil.

Analysis

The partial differential equation that governs transonic flow may be written as

$$[(1-M^2)-M^2(\gamma+1)\phi_x]\phi_{xx}+\phi_{yy}+\phi_{zz}$$
$$-2M^2\phi_{xt}-M^2\phi_{tt}=0 \tag{1}$$

with M as the freestream Mach number, and ϕ as the perturbation potential. Here, the flow is assumed to be unsteady, inviscid, and compressible past a thin wing at a small angle of attack. The wing lies in the x-y plane with the wind axis parallel to the x axis. The z axis coincides with the lift direction. The appropriate boundary conditions include the classical velocity tangency condition on the wing surface; the Kutta condition at the trailing edge, i.e., ϕ and its derivatives vanish approximately at infinity; and zero pressure difference across the plane $z=0$ at all regions outside of the wing.[11]

The MPD is not considered in detail here. Rubbert and Landahl[12] have described this method extensively. The thickness ratio ϵ of the wing section is used as the parameter for the parametric differentiation. The transformation of Eq. (1) to the ϵ-space with

$$g=\frac{\partial\phi}{\partial\epsilon} \quad \text{and} \quad u=\frac{\partial\phi}{\partial x} \tag{2}$$

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