Instantaneous Velocity Measurements in a Vane-Excited Plane Jet

J. C. S. Lai* and J. M. Simmons†
University of Queensland, Brisbane, Australia

The effects of oscillating a vane in the potential core of a turbulent jet have been investigated for the low Strouhal number range of 0.0016-0.0048 by making instantaneous velocity measurements with phase-averaging techniques. Significant unsteady effects, in the form of jet flapping, in the presence of harmonics, and non-similar profiles, are described. At the measured streamwise stations, entrainment and jet spreading increases significantly with increasing frequency and amplitude of vane oscillation compared with the corresponding steady jet values.

Nomenclature

F = peak-to-peak velocity variation expressed as a percentage of mean velocity
f = frequency of vane oscillation, Hz
h = nozzle width
$Q(x) = \int_{-\infty}^{\infty} \bar{U} \mathrm{d}y$
Q_E = nozzle volume flow per unit nozzle length
Re = Reynolds number, $\bar{U}_{ce}h/\nu$
St = Strouhal number, $fh/\bar{U}_{ce}$
t = time
T = period of vane oscillation
$\bar{U}$ = mean streamwise velocity
$\bar{U}_{ce}$ = mean nozzle exit centerline velocity
$\tilde{U}$ = ensemble-averaged streamwise velocity
u' = streamwise turbulence fluctuation
x = streamwise coordinate
x_ℓ = distance of leading edge of vane from nozzle
y = transverse coordinate
$y_{1/2}$ = jet half-width [distance from centerline to the location where $\bar{U}/\bar{U}_c = 0.5$ for mean velocity profile, or $\tilde{U}(x,y,\tau)/\tilde{U}_c(\tau) = 0.5$ for profile sampled at time τ]
ϵ = zero-to-peak amplitude of vane oscillation, deg
ν = kinematic viscosity
τ = sampled time

Subscripts

c = at centerline
$1/2$ = at jet half-width

Introduction

DESPITE extensive studies and documentation of the steady turbulent plane jet, notably by Heskestad,[1] Bradbury,[2] Everitt and Robins,[3] and Gutmark and Wygnanski,[4] discrepancies exist among published results with regard to such parameters as spreading and velocity decay rates. However, in most engineering situations, "truly" steady turbulent jets do not exist and unsteadiness of varying degrees occurs in various ways, for example, flapping due to large-scale structures or initial exit conditions (as reported by Cervantes and Goldschmidt[5]) and puffing due to an unsteady blower. The demonstration of the existence of large-scale coherent structures superimposed on a background of "turbulence" in a plane mixing layer by Brown and Roshko[6] has stirred great interest in the fluid mechanics community to identify similar structures in other flows and determine their roles in constructing the characteristics of the flowfield.

With the advent of improved computer technology and measurement techniques, it is possible to introduce perturbations into the flow artificially to enhance the naturally occurring large-scale coherent structures that can be studied using conditional sampling techniques.[7] Results of such controlled perturbation experiments can provide an improved understanding of fundamental phenomena such as the structure of turbulence, shear-layer instability, and natural entrainment processes. On the other hand, perturbations introduced at any arbitrary frequency may produce non-naturally occurring structures which subsequently influence the flowfield. In cases where such perturbations enhance mixing and entrainment, they have important applications in areas such as fluidics, combustion, and thrust-augmenting ejectors for VSTOL aircrafts. The present investigation stems from a quest for an efficient method to increase plane jet entrainment for practical applications.

In order to study the structure of a turbulent axisymmetric jet, Crow and Champagne[8] introduced acoustic excitation at a Strouhal number St of 0.3 and root-mean-square (rms) amplitude of $0.02\bar{U}_{ce}$. Significant increases in entrainment (up to 32% at 8 nozzle diameters downstream of the nozzle) were reported. Large-scale orderly structures in the form of toroidal vortices have been identified by Crow and Champagne[8] and Zaman and Hussain,[9] and $St = 0.3$ has been regarded as the "preferred" frequency at which an axisymmetric distrubance receives maximum amplification in the jet column. However, Zaman and Hussain[9,10] reported that, under certain conditions of excitation ($St = 1.3$-2.4), turbulence intensities in both axisymmetric and plane jets can be reduced. Therefore, caution must be taken to perturb a jet at the right condition if enhancement of mixing is the primary objective. Although a flow-visualization study by Rockwell and Niccolls[11] tends to suggest the existence of coherent large-scale structures in plane jets, it is only recently that more evidence has been provided by Oler and Goldschmidt,[12] Thomas and Goldschmidt,[13] and Moum et al.[14]

Various means of jet excitation have been reported in the literature, such as acoustic excitation,[8,9,13,15-17] fluidic excitation,[18,19] and mechanical excitation.[20-23] In general, acoustic excitation can be introduced at very high frequency but low excitation amplitude, giving a Strouhal number on the order of 1. On the other hand, fluidic and mechanical excitation generally involve lower frequencies, producing Strouhal numbers much smaller than 1, although the excitation amplitude can be much larger than in the acoustic case. Even

Received Nov. 21, 1983; revision received Sept. 17, 1984.

*Lecturer/Research Fellow, Department of Mechanical Engineering. Member AIAA.
†Reader, Department of Mechanical Engineering. Member AIAA.

Table 1 Summary of unsteady turbulent plane jet experiments

Source	h (mm)	Aspect Ratio	Re	St	ε	Side Plates to contain Jet	Measured x/h	Excitation Means	Remarks
				Streamwise Excitation					
Hussain & Thompson[15]	31.8	44	8×10^3 to 3.1×10^4	0.15 to 0.6	$0.014\overline{U}_{ce}$	Yes	0-15	Acoustic - settling chamber upstream of nozzle excited by a loud speaker	Hot-wire measurements show insignificant difference between steady and excited jet
Lai & Simmons[22]	5	60	1.1×10^4	0.0001 to 0.003	0.075 to $0.105\overline{U}_{ce}$	Yes	0-80	Mechanical - mass flow perturbation by bleeding off air upstream of nozzle	
Rockwell & Nicolls[11]	-	-	2800	0.52	$1.1\ \overline{U}_{ce}$	Yes	0-5	Mechanical - varying flow cross-sectional area upstream of nozzle	Flow visualization shows vortex pairing in near field region
				Transverse Excitation					
Binder & Favre-Marinet[19]	10	150	0.85×10^4	0 to 0.062	0 to 8°	Yes	0-100	Fluidic - flapping of jet by Coanda effect	X-wire measurements show increase in jet spreading and velocity decay
Chambers & Goldschmidt[17]	6.35	48	6000	0.1 to 1	105 dB SPL	Yes	0-40	Acoustic - jet excited by horn just outside the nozzle	Pitot tube data show increase in jet spreading and velocity decay
Galea & Simmons[23]	5	60	1×10^4	0.0033 to 0.0125	0.025 to 0.09 $\overline{U}_{ce}$	No	0-40	Mechanical - jet excited by sinusoidal nozzle area variation	Hot wire data show 50% increase in entrainment at x/h = 20
Piatt & Viets[18]	12.7	-	3.2×10^4	0.0013 to 0.0009	-	No	0-40	Fluidic - flapping of jet by Coanda effect	X-wire data show increase in jet spreading
Simmons et al[21]	0.38	1210	1.4 to 3.9×10^5	0.00001 to 0.00014	0° to 15°	No	0-100	Mechanical - Jet deflection by oscillation of nozzle	Hot wire data show negligible difference between steady and excited jet
Simmons et al[24]	6	50	1.4×10^4	0.0008 to 0.0049	2.6° 5.2°	No	0-60	Mechanical - Jet excited by forced oscillation of a vane in potential core	Hot wire data show 100% increase in entrainment at x/h = 20.

though the means of excitation has a strong influence on the flow development of the excited jet, it is more appropriate to categorize the excitation according to the direction in which it is introduced; that is, streamwise and transverse excitations.

Table 1 summarizes some of the information from excited plane jet studies. For streamwise excitation, a flow-visualization study was conducted by Rockwell and Niccolls[11] of a plane jet excited by perturbing the flow cross-sectional area upstream of the plenum-jet nozzle combination at $St = 0.52$, yielding essentially sinusoidal flow at the nozzle exit. Although photos of the flow at this low Reynolds number (2800) tend to show vortex pairing, no quantitative results on the flow characteristics have been reported. The studies by Lai and Simmons[22] of a mechanically excited jet over a Strouhal number range of $0.0001 \leq St \leq 0.003$, and by Hussain and Thompson[15] of an acoustically excited jet for $0.15 \leq St \leq 0.6$ indicate insignificant differences in the flow characteristics between the steady and excited jets. Thus, streamwise excitation appears to be an ineffective means of enhancing entrainment in a plane jet.

To obtain transverse excitation, the jet of Simmons et al.[21] was excited by periodic oscillation of the nozzle through small angles for $0.00001 \leq St \leq 0.00014$. At these very low Strouhal numbers, the results indicate that the excited jet can be described by a quasisteady model. However, in other studies with transverse excitation, the acoustically excited jets of Fiedler and Korschelt[16] and Chambers and Goldschmidt,[17] the fluidically excited jets of Piatt and Viets[18] and Binder and Favre-Marinet,[19] and the mechanically excited jet of Galea and Simmons[23] all indicate significant increases in jet spreading rate, velocity decay rate, and jet entrainment. These studies cover the Strouhal number range of $0.0009 \leq St \leq 1$ and the excitation has been introduced asymmetrically. Fiedler and Korschelt[16] observed very little effect when the excitation was applied symmetrically.

Preliminary mean velocity measurements made by Simmons et al.,[24] Collins et al.,[25] and Badri Narayanan and Raghu[26] of a vane-excited jet (transverse excitation) show substantial increases in jet entrainment without loss in nozzle efficiency for a nozzle pressure ratio range of 1.008-1.268. These results are supported by the thrust measurements of McClellan[27] and Badri Narayanan and Raghu[28] who reported thrust increases in an ejector fitted with a similar excitation device in the primary jet.

The objectives of this investigation were to explore the instantaneous velocity field of the vane-excited plane jet in more detail and study the effects of transverse perturbation on the behavior of a turbulent jet at low Strouhal numbers.

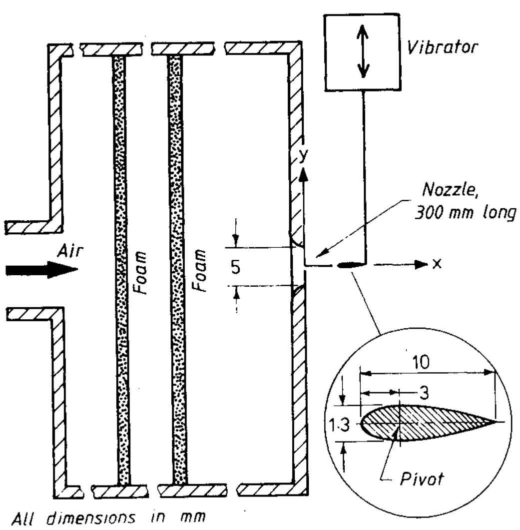


Fig. 1 Schematic of vane-excited jet facility (not to scale).

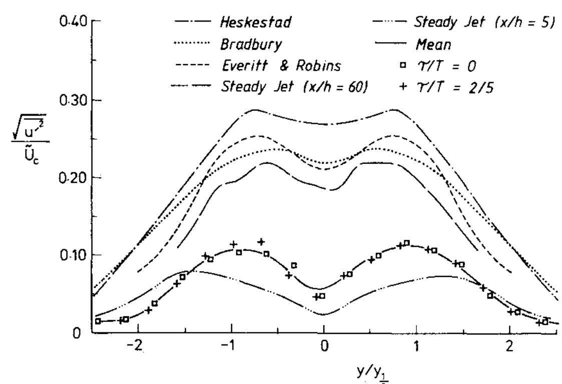
Experimental Apparatus and Procedure

Apparatus

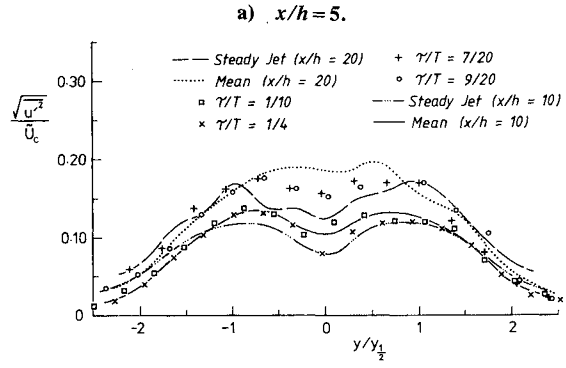
Measurements in both steady and unsteady jets were made in the facility shown schematically in Fig. 1. The jet of air issued into stationary air from a rectangular nozzle with profiles based upon British standard BS1042.[29] The nozzle dimensions were: length $\ell = 300$ mm, width $h = 5$ mm, and aspect ratio = 60. 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%. No side plates were used to enhance the two-dimensionality of the jet, but the variation of velocity over the central 50 mm portion of the length of the steady jet was less than 4% at 100 nozzle widths downstream of the nozzle. In the unsteady jet, excitation was introduced in the transverse (y) direction by using an electromagnetic vibrator to oscillate a vane with variable amplitude and frequency in pitch about an axis 3 mm aft of its leading edge (Fig. 1). The vane had a symmetric airfoil section 1.3 mm thick, a span of 360 mm, and a chord of 10 mm. It was located symmetrically in the potential core of the steady jet with its leading edge at a distance x_ℓ from the nozzle. The mean jet exit Reynolds number was 1×10^4. The various tested conditions are listed in Table 2.

Instrumentation

Instantaneous velocity measurements across the jet and up to 60 nozzle widths downstream of the nozzle were obtained with a DISA 55P51 X-wire probe, a DISA 55H26 probe support, and two DISA 55M constant-temperature hot-wire anemometers. The X-wire sensor was made of copper-plated tungsten wire with a working section 5 μm in diameter and 1.5 mm long. It was operated at a resistance ratio of 1.3. The wires were calibrated in a facility which provided uniform flow with low turbulence and angular rotation of the probe for angular sensitivity calibration. The X-wire was



a) $x/h = 5$.



b) $x/h = 10$ **and 20.**

Fig. 2 Phase-averaged streamwise turbulence profiles for test 20S2.

aligned in the test rig to ensure the same orientation as in the calibration.

The sinusoidal output of the function generator which drove the electromagnetic vibrator was also used to provide a reference signal for applying phase-averaging techniques. The two linearized hot-wire anemometer outputs and the reference signal were stored with an FM tape recorder, with a recording bandwidth of 1250 Hz.

Data Analysis

Data analysis was performed on an EAI600 hybrid computing system. The recorded linearized hot-wire anemometer outputs were separated on the analog computer to yield the instantaneous velocity components U_i and V_i in the streamwise and transverse directions, respectively. By means of the usual triple decomposition, U_i can be written in terms of a mean component $\bar{U}$, a periodic fluctuating component u, defined here as "pseudoturbulence," and the intrinsic turbulent fluctuation u' as follows:

$$U_i = \bar{U} + u + u' \tag{1}$$

By using the reference signal $A\sin 2\pi ft$ for timing, it was possible to study the velocity field at each of 20 sample times $t=\tau_i$ during one period $T=1/f$ of vane oscillation, where τ_i is given by

$$\tau_i = (i-1)T/20, \qquad i=1,2,\ldots,20 \tag{2}$$

The positive 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 U_i. About 900 successive ensembles were sampled at each τ_i and stored in a normalized histogram with 401 cells to calculate the ensemble-averaged velocity.

$$\tilde{U}_i(\tau_i,x,y) = E(U_i) \tag{3}$$

where E is the ensemble expectation operator and

$$\tilde{U}_i(\tau_i,x,y) = \bar{U} + u \tag{4}$$

The distribution of $\tilde{U}_i$ over y for a given x and τ_i is referred to here as a phase-averaged velocity profile. Mean (time-averaged) velocity profiles were obtained by averaging the phase-averaged velocity profiles at a given x over all 20 sample times τ.

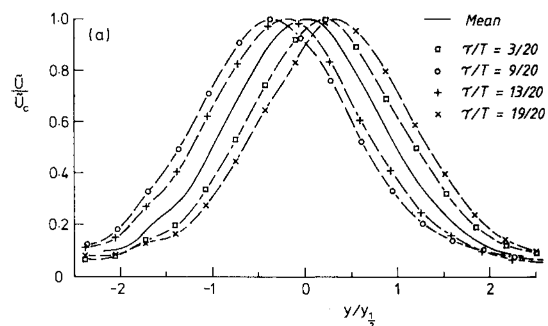
The X-wire measurements of the streamwise velocity profiles of the steady jet have been compared with pitot tube measurements and the agreement is within 5%. However, for the transverse velocity (V_i) measurements, there is a greater uncertainty (on the order of 10-15%). This is primarily because V_i is a small quantity and is obtained as a difference between two quantities of similar magnitude. Nevertheless, the mean transverse velocity profiles for the vane-excited jet do not differ significantly from those of the steady jet within the limits of accuracy of the experimental techniques. This result agrees with the independent measurements in a similar jet facility made by Harch et al.[31] using two-color laser Doppler velocimetry. For this reason, only streamwise velocity and turbulence profiles are presented in the following sections.

Results and Discussions

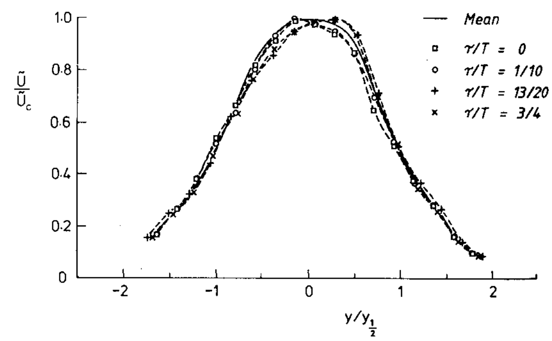
Steady Jet

The mean flow measurements for the steady jet fall within the range of those published in the literature. The nondimensional mean velocity profiles compare well with the Goertler solution. However, as shown in Fig. 2a, the nondimensional streamwise turbulence intensity profile is slightly lower than those reported by Heskestad,[1] Bradbury,[2] and Everitt and Robins,[3] but repeated measurements produced the same results. A review of the turbulence data in the literature reveals a typical spread of 30% for the turbulence profiles. Hence, the jet facility used is a good basis for unsteady turbulent plane jet experiments.

Preliminary single-wire measurements have shown that, for streamwise distances larger than 5-10 nozzle widths from the nozzle, the flowfield of a jet with the presence of a stationary vane located at $x_\ell/h=1.66$ is not significantly different from that without the presence of a vane. Hence, in what follows, the term "steady jet" refers to a jet without the presence of a vane.



a) $x/h=20$ for test 10S2.



b) $x/h=60$ for test 30S1.

Fig. 3 Phase averaged velocity profiles.

Table 2 Test conditions

Test[a]	10S1	20S1	30S1	10L1	20L1	30L1	10S2	20S2
f, Hz	10	20	30	10	20	30	10	20
$St=fh/\bar{U}_{ce}$	0.0016	0.0032	0.0048	0.0016	0.0032	0.0048	0.0016	0.0032
ϵ(zero-peak), deg	2.6	2.6	2.6	5.2	5.2	5.2	2.6	2.6
x_ℓ/h	0.66	0.66	0.66	0.66	0.66	0.66	1.66	1.66

[a]The test code consists of a double digit (which indicates the frequency), followed by "S" (for $\epsilon=2.6$ deg) or "L" (for $\epsilon=5.2$ deg) and a single digit "1" (for $x_\ell/h=0.66$) or "2" (for $x_\ell/h=1.66$).

Vane-Excited Jet

Phase-Averaged and Mean Velocity Profiles

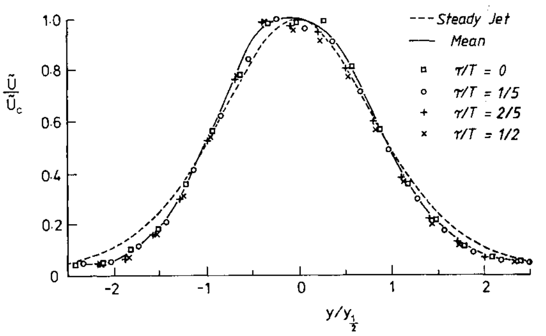
It is obvious that the oscillation of the vane tends to deflect the jet about a mean position and, consequently, the instantaneous location of the jet's centerline oscillates with time. That is, a flapping motion of the jet is produced. If a quasisteady jet model is applied to a vane-excited jet without consideration of dynamic effects, 2.6 and 5.2 deg zero-to-peak oscillations of the vane will be assumed to deflect the jet by the same amount; when expressed in terms of jet half-width, the jet will oscillate about a mean position with a zero-to-peak amplitude of 0.4 and $0.8y_{1/2}$, respectively. The nondimensional phase-averaged velocity profiles for $f=10$ Hz in Fig. 3a show the phase-averaged centerline for various times τ. They not only confirm the action of a flapping motion of the jet, but also indicate that the deflection from the centerline of the mean velocity profile is about 0.4-$0.5y_{1/2}$ for a 2.6 deg oscillation. Phase-averaged velocity profiles for other frequencies and $x/h<40$ generally follow the same pattern. Figure 4 shows that when the centerlines of the phase-averaged velocity profiles are plotted coincident with the centerline of the mean velocity profile, the phase-averaged velocity profiles collapse onto the mean velocity profile. The steady jet profile at the corresponding streamwise distance from the nozzle is also shown. The results are typical of all test cases with occasional exceptions for streamwise distances larger than $x/h=20$. For example, at $x/h=40$, the mean velocity profiles exhibit a slight double peak and the phase-averaged velocity profiles cannot be made to collapse onto the mean velocity profile.

For all test cases at $x/h=5$ (see, for example, Fig. 4a), the mean velocity profile is "flatter" in the vicinity of the centerline than the corresponding steady jet profile, as if the potential core has been lengthened. However, the velocity decay plot in Fig. 7b suggests otherwise. Hence, this result is attributed to the rapid mixing that occurs near the centerline due to the proximity of the vane to the measurement location.

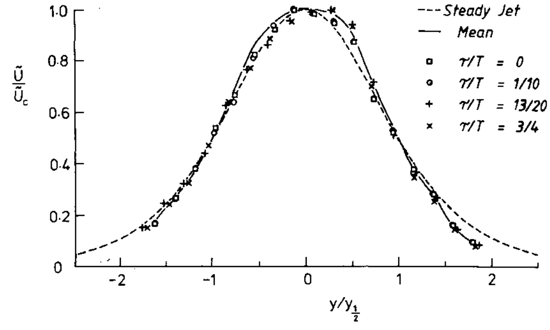
For a 5.2 deg amplitude of vane oscillation or for frequencies of vane oscillation greater than 10 Hz, the flapping action of the jet is less pronounced at $x/h=60$ than at smaller streamwise distances from the nozzle. As displayed in Fig. 3b for the test case 30S1, the amplitude of jet flapping is only $0.25y_{1/2}$ compared with $0.4y_{1/2}$ predicted by a quasisteady jet model. This indicates rapid mixing of entrained air with that in the neighborhood of the centerline. This phenomenon is certainly supported by the nondimensional mean velocity profile which is "flatter" than the corresponding steady jet profile (Fig. 4b). Similar behavior was detected by the two-color laser-Doppler velocimeter measurements of the mean velocity profile of a similar vane-excited jet by Harch et al.[31] These results not only differ significantly from the prediction of a quasisteady jet model but they also suggest that multiple length scales are probably required for the description of such an unsteady flowfield.

Phase-Averaged Velocity Variation at the Centerline and Half-Width of the Mean Velocity Profile

In order to examine closely the effects of excitation on the jet behavior, the phase-averaged velocity variation for each streamwise measurement station is analyzed at two points, namely, the centerline (CLM) and jet half-width (HWM) of the mean velocity profile. Figure 5a displays the variation of the phase averaged velocity at the CLM for test 20S2. The behavior of the jet at other test conditions is similar. Except for $x/h=5$, it is evident that harmonics appear in the velocity variation at the CLM where, in some cases, e.g., $x/h=40$, the second harmonic seems to be even more dominant than the fundamental at the frequency of vane oscillation. This result can be due to the combined effect of some structures occasionally extending beyond the CLM and the flapping action of the jet. The general trend of the velocity variation is amplification of the excitation at $x/h>5$, followed by a frequency dependent decay rate. The velocity variation can be characterized by a parameter F_c that expresses the peak-to-peak variation of the velocity at CLM as a percentage of the mean velocity. The variation of F_c with x/h is plotted in Fig. 6a for various test conditions. For $\epsilon=2.6$ deg, with the exception $f=10$ Hz where the excitation is still being amplified at $x/h=60$, F_c reaches a maximum at

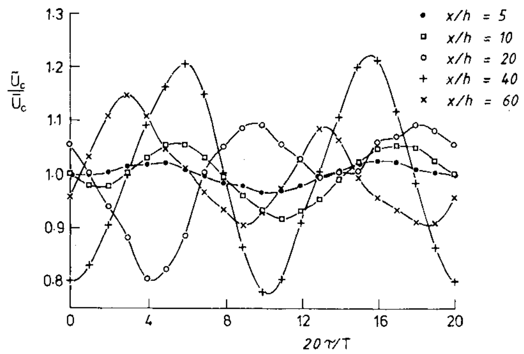


a) $x/h=5$ for test 20S2.

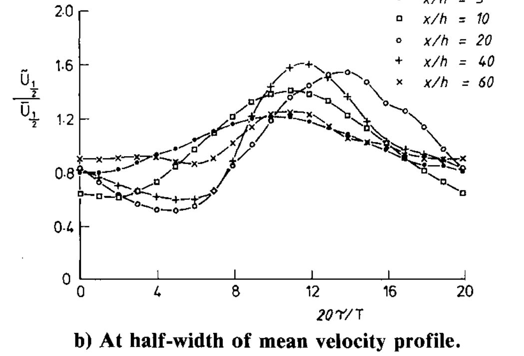


b) $x/h=60$ for test 30S1.

Fig. 4 Nondimensional velocity distribution.



a) At centerline of mean velocity profile.



b) At half-width of mean velocity profile.

Fig. 5 Phase-averaged velocity variation for test 20S2.

$x/h = 40$, which is independent of the locations of the vane tested here. For $\epsilon = 5.2$ deg, F_c also reaches a maximum at $x/h = 40$ for $f = 10$ and 20 Hz whereas this location moves upstream to $x/h = 20$ for $f = 30$ Hz. This is consistent with the expectation that the higher the frequency, the closer the streamwise distance to the nozzle at which the excitation attains maximum amplification. That there is no difference in the location of maximum amplification for F_c at other frequencies may be due to the large separation between two streamwise measurement stations. Maximum amplification actually may occur somewhere between the measurement stations. The phase-averaged velocity variation at the CLM is very much different from the prediction of a quasisteady model which gives a maximum F_c of 11 and 44% for $\epsilon = 2.6$ and 5.2 deg, respectively, compared with the experimental values of 47 and 88%.

The phase-averaged velocity variation at the jet half-width (HWM) of the mean velocity profile for test 20S2 is shown in Fig. 5b. It is immediately obvious that, contrary to the variation of the velocity at the CLM, the fundamental frequency of vane oscillation plays the major role here. This is perhaps because any structures which arise from turbulent-nonturbulent interface interactions tend to cover the HWM most of the time and only extend beyond the CLM occasionally. The parameter $F_{1/2}$ is defined similarly to F_c at the HWM. The location where $F_{1/2}$ reaches maximum is closer to the nozzle than that for F_c, being at $x/h = 20$ for $\epsilon = 2.6$ deg and $x/h = 10$ for $\epsilon = 5.2$ deg (Fig. 6b). Again, with the exception of $f = 10$ Hz and $\epsilon = 2.6$ deg, this location of maximum $F_{1/2}$ appears to be independent of the frequency of vane oscillation. However, it is strongly suspected that this is a result of the large separation between discrete measurement stations, as mentioned above. The results certainly suggest that maximum amplification of excitation at the HWM diffuses toward the CLM, yielding a maximum amplification of excitation at the CLM at a further distance downstream of the nozzle. Some structures may be responsible for this effect, although their identification will require further exploration. A quasisteady model only predicts a $F_{1/2}$ of 103 and 165% for $\epsilon = 2.6$ and 5.2 deg, respectively, compared with 114 and 184% for the experimental data.

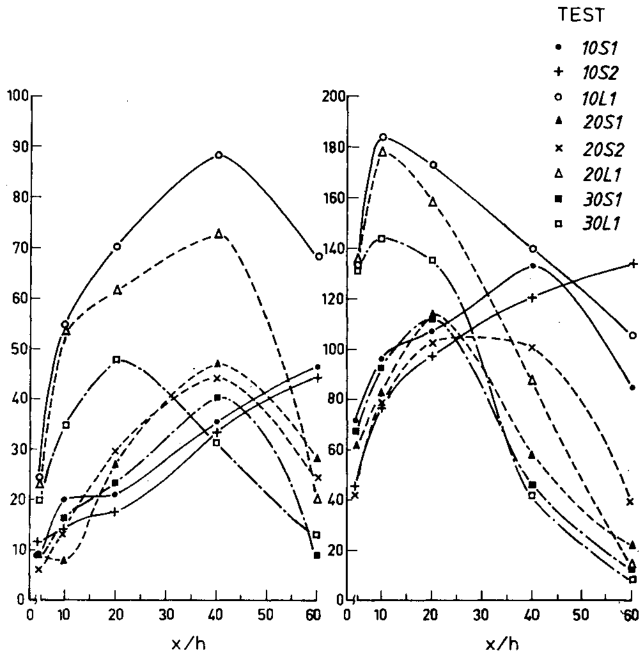
Phase-Averaged and Mean Streamwise Turbulence Profiles

The instantaneous and mean streamwise turbulence profiles for test case 20S2 are plotted in Fig. 2 for various streamwise measurement stations. The mean turbulence intensities are significantly higher than the corresponding steady jet values for $x/h < 60$, indicating perhaps considerable mixing has taken place. Except near the centerline, the nondimensional phase-averaged streamwise turbulence profiles collapse onto the mean profiles at streamwise measurement stations closer to the nozzle, for example, at $x/h < 40$.

However, at $x/h = 40$, where maximum amplification of excitation is attained (Fig. 6a), not only is the mean profile very different in shape from the corresponding steady jet profile near the centerline, but also the phase averaged profiles cannot be made to collapse onto the mean profile. Again, this suggests the possibility of the existence of multiple length scales arising from interaction of the flapping motion with turbulent structures. At $x/h = 60$, the excitation has decayed and the mean turbulence profile resembles that of the steady jet profile, although the phase-averaged profiles are still different from the mean profile. The results discussed are typical of other test conditions listed in Table 2 and reveal the importance of unsteady effects which cannot be predicted with a quasisteady model.

Jet Spreading Rate, Velocity Decay Rate, Entrainment, and Momentum Consideration

The unsteady effects described previously are manifested in certain parameters such as jet spreading rate and velocity



a) F_c. b) $F_{1/2}$.

Fig. 6 Variation of F_c and $F_{1/2}$ with streamwise distance.

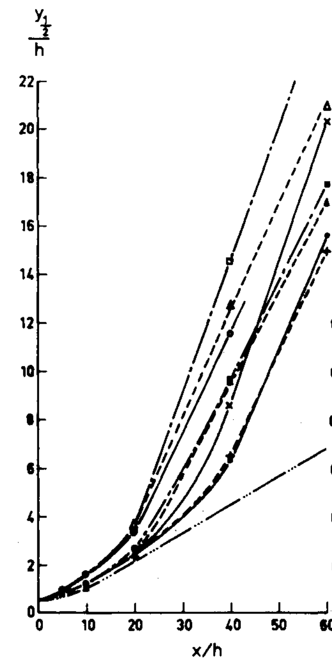


Fig. 7a Variation of jet spreading with streamwise distance.

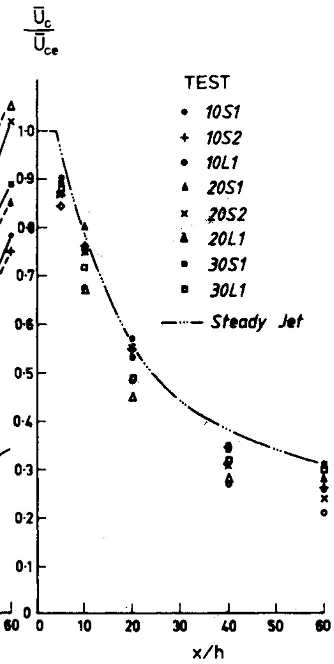


Fig. 7b Variation of centerline velocity decay with streamwise distance.

decay rate. Figure 7a depicts the variation of the jet half-width of the mean velocity profile with streamwise distance whereas Fig. 7b displays the decay of the mean velocity at the centerline of the mean velocity profile with streamwise distance for various test conditions. Although the data are sparse in the range of $x/h > 40$, lines are drawn in Fig. 7a to indicate the spreading trend. Furthermore, the absence of confining plates in the jet facility may give rise to three-dimensional effects at $x/h > 40$. Hence, emphasis should be placed on interpreting the data for $x/h < 40$. In general, faster jet spreading is produced by high frequency and large amplitude vane oscillation. There also appears to be a shift in geometric virtual origin. However, the effect on velocity decay is not as obvious although the mean centerline velocity

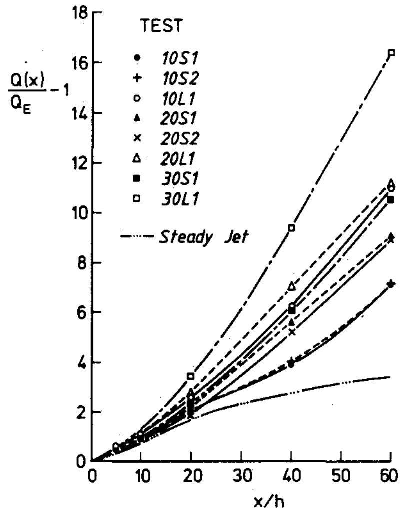


Fig. 8 Variation of entrainment with streamwise distance for all test conditions.

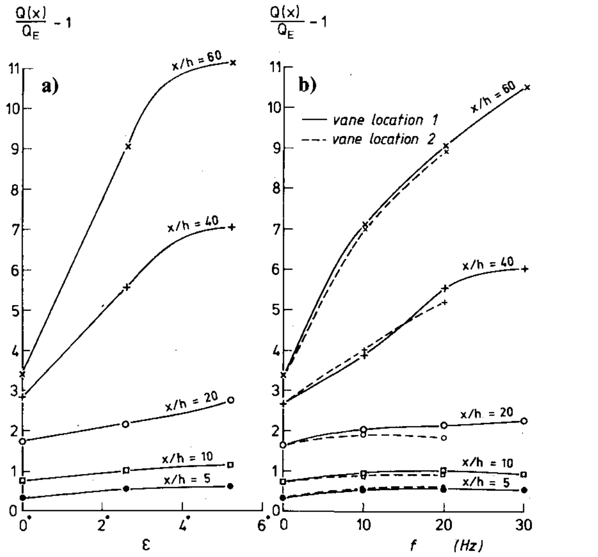


Fig. 9 Variation of entrainment with a) amplitude of vane oscillation for test 20S1, and b) frequency of vane oscillation for $\epsilon = 2.6$ deg.

for the excited jet generally is lower than the corresponding steady jet value.

There has been much controversy about the actual mechanism of entrainment,[32] but entrainment is generally regarded as the process by which irrotational fluid in the surrounding area is assimilated into the jet and becomes rotational. Since vorticity measurements are required to correctly identify the entrained fluid and are rarely performed, a simpler definition of entrainment is given by $[Q(x) - Q_E]/Q_E$. Here $Q(x)$ is the volume flow per unit width at a streamwise station x obtained by integrating the corresponding mean velocity profile, and Q_E is the nozzle volume flow per unit nozzle length. As already pointed out by other investigators of jet entrainment, for example, Crow and Champagne,[8] the termination of the integration at the jet boundaries requires some care because of the inherent uncertainty of hot-wire measurements near the edge of the jet. In the steady jet, the jet boundaries conventionally are regarded as terminated at $y/y_{1/2} = 2$. However, in the vane-excited jet, the determination of the jet boundaries is not as simple because of the wider spreading of the jet and suspected flow reversal which may be more severe than the corresponding steady jet. Nevertheless, in order to indicate the "approximate entrainment" obtained with the vane-excited jet, the integration has been performed with the profile terminated at $y/y_{1/2} = 2$ and with the jet edge region beyond this point obtained by linear extrapolation. The variation of the entrainment with streamwise distance is shown in Fig. 8 for various test conditions and is compared with the corresponding steady jet value. Significant increase in entrainment is achieved; for example, at $x/h = 20$ and for $f = 30$ Hz and $\epsilon = 5.2$ deg, the entrainment is 100% higher than that of the steady jet. Figure 9a reveals the typical effect of vane amplitude of oscillation on entrainment for test case 20S1. Higher amplitude of vane oscillation produces higher entrainment. The effect of frequency of vane oscillation and vane location on entrainment is shown in Fig. 9b. It appears that the two vane locations tested yield essentially the same values of entrainment. For a streamwise distance less than 20 nozzle widths, the frequency effect on entrainment is less obvious, but for a larger streamwise distance, higher frequency produces higher entrainment.

Momentum conservation in a turbulent jet has been a subject of debate ever since experimental measurements tended to indicate otherwise, even for the steady case.[30] In an acoustically excited jet, Hussain and Thompson[15] reported a 33% variation over a streamwise distance of 15 nozzle widths for the integral defined by

$$M = \int_{-\infty}^{\infty} \bar{U}^2 \mathrm{d}y / \bar{U}_{ce}^2 h \tag{5}$$

In the vane-excited jet, for $x/h \leq 20$, M varies by less than 29%. For larger streamwise distances, the variation of M over 40 nozzle widths can be as low as 17% for test 10S1 or as high as 74% for test 20L1. The result is quite consistent with the measurements of Hussain and Thompson.[15]

Conclusions

An asymmetrical, transverse excitation has been introduced into a steady turbulent jet by forced oscillation of a vane located in the potential core. Instantaneous two-component velocity measurements confirm the existence of a very strong flapping action. Streamwise turbulence intensities are significantly higher than those in the steady jet, indicating enhanced mixing due to the interaction of the flapping motion with turbulence structures. Significant departure of phase-averaged velocity and turbulence profiles from the similar profiles are observed for certain conditions such as where maximum amplification of the effect of excitation occurs. The fundamental component of excitation is dominant in the behavior of the jet at the half-width, whereas harmonic effects play a more important role in the vicinity of the jet centerline. These unsteady effects cannot be predicted using quasisteady approximations and present an exciting test case for numerical modeling.

The integral result of the unsteady effects is manifested in a significant increase in jet entrainment and spreading with increasing frequency and amplitude of vane oscillation. The exact mechanism by which the flapping motion of the jet interacts with turbulence to produce such results requires more detailed correlation measurements and flow-visualization studies to identify the existence of any large-scale structures. The results demonstrate that this type of excitation is very effective in producing jet entrainment increases at low Strouhal numbers where nozzle efficiency can be maintained and losses can be minimized.

Acknowledgments

This project was supported by Australian Research Grants Scheme and a special grant from the University of Queensland. The authors are grateful to Prof. V. W.

Goldschmidt for his constructive criticism and comments on the draft of the manuscript.

References

[1]Heskestad, G., "Hot-Wire Measurements in a Plane Turbulent Jet," *Journal of Applied Mechanics, Transactions of ASME*, Vol. 32, 1965, pp. 721-734.

[2]Bradbury, L. J. S., "The Structure of a Self-Preserving Turbulent Plane Jet," *Journal of Fluid Mechanics*, Vol. 23, 1965, pp. 31-64.

[3]Everitt, K. W. and Robins, A. G., "The Development and Structure of Turbulent Plane Jets," *Journal of Fluid Mechanics*, Vol. 88, 1978, pp. 563-583.

[4]Gutmark, E. and Wygnanski, I., "The Planar Turbulent Jet," *Journal of Fluid Mechanics*, Vol. 73, 1976, pp. 465-495.

[5]Cervantes, J. G. and Goldschmidt, V. W., "The Apparent Flapping Motion of a Turbulent Plane Jet—Further Experimental Results," *Journal of Fluids Engineering, Transactions of ASME*, Vol. 103, 1981, pp. 119-126.

[6]Brown, G. L. and Roshko, A., "On Density Effects and Large Structure in Turbulent Mixing Layers," *Journal of Fluid Mechanics*, Vol. 64, 1974, pp. 715-816.

[7]Antonia, R. A., "Conditioning Sampling in Turbulence Measurement," *Annual Reviews of Fluid Mechanics*, Vol. 13, 1981, pp. 131-156.

[8]Crow, S. C. and Champagne, F. H., "Orderly Structure in Jet Turbulence," *Journal of Fluid Mechanics*, Vol. 48, 1971, pp. 547-591.

[9]Zaman, K. B. M. Q. and Hussain, A. K. M. F., "Vortex Pairing in a Circular Jet under Controlled Excitation, Part 1. General Jet Response," *Journal of Fluid Mechanics*, Vol. 101, 1980, pp. 449-491.

[10]Zaman, K. B. M. Q. and Hussain, A. K. M. F., "Turbulence Suppression in Free Shear Flows by Controlled Excitation," *Journal of Fluid Mechanics*, Vol. 103, 1981, pp. 133-159.

[11]Rockwell, D. O. and Niccolls, W. O., "Large Amplitude Axial Excitation of Planar Jet Flow," *Journal of Fluids Engineering, Transactions of ASME*, Vol. 97, 1975, pp. 380-382.

[12]Oler, J. W. and Goldschmidt, V. W., "A Vortex-Street Model of the Flow in the Similarity Region of a Two-Dimensional Free Turbulent Jet," *Journal of Fluid Mechanics*, Vol. 123, 1982, pp. 523-535.

[13]Thomas, F. O. and Goldschmidt, V. W., "Interaction of an Acoustic Disturbance and a Two-Dimensional Turbulent Jet: Experimental Data," *Journal of Fluids Engineering, Transactions of ASME*, Vol. 105, pp. 134-139.

[14]Moum, J. N., Kawall, J. G., and Keffer, J. F., "Coherent Structures within the Plane Turbulent Jet," *The Physics of Fluids*, Vol 26, 1983, pp. 2939-2945.

[15]Hussain, A. K. M. F. and Thompson, C. A., "Controlled Symmetric Perturbation of the Plane Jet: An Experimental Study in the Initial Region," *Journal of Fluid Mechanics*, Vol. 100, 1980, pp. 397-431.

[16]Fiedler, H. and Korschelt, D., "The Two Dimensional Jet with Periodic Initial Condition," *Proceedings of 2nd Symposium on Turbulent Shear Flows*, Imperial College, U.K., July 1979, pp. 334-339.

[17]Chambers, F. W. and Goldschmidt, V. W., "Acoustic Interaction with a Turbulent Plane Jet: Effects on Mean Flow," *AIAA Journal*, Vol. 20, June 1982, pp. 797-804.

[18]Piatt, M. and Viets, H., "Conditional Sampling in an Unsteady Jet," AIAA Paper 79-1857, Aug. 1979.

[19]Binder, G. and Favre-Marinet, M., "Some Characteristics of Pulsating or Flapping Jets," *Unsteady Turbulent Shear Flows*, edited by R. Michel, J. Cousteix, and R. Houdeville, Toulouse, France, May 1981, Springer-Verlag, Berlin, pp. 370-379.

[20]Binder, G. and Favre-Marinet, M., "Mixing Improvement in Pulsating Turbulent Jets," *Proceedings of ASME Symposium in Fluid Mechanics of Mixing*, Atlanta, Ga., June 1973, pp. 162-172.

[21]Simmons, J. M., Platzer, M. F., and Smith, T. C., "Velocity Measurements in an Oscillating-Plane Jet Issuing into a Moving Stream," *Journal of Fluid Mechanics*, Vol. 84, pp. 33-53.

[22]Lai, J. C. S. and Simmons, J. M., "Instantaneous Velocity Measurements in a Periodically Pulsed Plane Turbulent Jet," *AIAA Journal*, Vol. 18, Dec. 1980, pp. 1532-1534.

[23]Galea, S. C. and Simmons, J. M., "Excitation of a Plane Jet by Periodic Perturbation of the Nozzle Area," *Proceedings of 8th Australasian Fluid Mechanics Conference*, Newcastle, Australia, Nov. 1983, pp. 13C·5-13C·8.

[24]Simmons, J. M., Lai, J. C. S., and Platzer, M. F., "Jet Excitation by an Oscillating Vane," *AIAA Journal*, Vol. 19, June 1981, pp. 673-676.

[25]Collins, D. J., Platzer, M. F., Lai, J. C. S., and Simmons, J. M., "Experimental Investigation of Oscillating Subsonic Jets," *Numerical and Physical Aspects of Aerodynamic Flows*, edited by T. Cebeci, Springer-Verlag, New York, 1982, Chap. 33.

[26]Badri Narayanan, M. A. and Raghu, S., "Two-Dimensional Jet Subjected to Periodic Oscillations in the Potential Core Region," Fluid Dynamics Lab., Dept. of Aeronautical Engineering, Indian Institute of Science, Bangalore, India, Rept. 82 FM2, March 1982.

[27]McClellan, T. R., "Experimental Investigation of Thrust Augmenting Ejectors Using Vane Excited Primary Jets," Masters Thesis, Naval Postgraduate School, Monterey, Calif., 1982.

[28]Badri Narayanan, M. A. and Raghu, S., "Effect of Excitation of the Primary Jet on Ejector Thrust Augmentation," Fluid Dynamics Lab., Indian Institute of Science, India, Rept AE82, FM11, 1982.

[29]"Methods for Measurement of Fluid Flow in Pipes," British Standards Institution, London, U.K., Rept. BS1042, Pt. 1, 1964, p. 141.

[30]Hussain, A. K. M. F. and Clark, A. R., "Upstream Influence on the Near Field of a Plane Turbulent Jet," *The Physics of Fluids*, Vol. 20, 1977, pp. 1416-1426.

[31]Harch, W., Collins, D. J., and Platzer, M. F., "A Description of the Velocity Field of a Vane Excited Turbulent Jet," *Proceedings of 8th Australasian Fluid Mechanics Conference*, Newcastle, Australia, Nov. 1983, pp.8C·5-8C·8.

[32]Bremhorst, K. and Harch, W. H., "The Mechanisms of Jet Entrainment," *AIAA Journal*, Vol. 16, Oct. 1978, pp. 1104-1106.