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Acoustic Interaction with a Turbulent Plane Jet: Effects on Mean Flow

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The effects of pure tone acoustic fields upon the mean flow in a low Reynolds number turbulent plane jet were investigated experimentally. It was found that the main region flow can be altered by moderate level disturbances over a range of disturbance frequencies. The effects were observed to extend to distances of 80 nozzle widths downstream of the nozzle, while decaying with downstream distance, and to be linked to the turbulence behavior of the initial region shear layers.

Nomenclature

B = jet velocity half-width
C_1 = virtual origin of jet widening (geometric origin)
C_2 = virtual origin of jet centerline velocity decay (velocity origin)
D = jet nozzle slot width or diameter
K_1 = jet widening rate
K_2 = jet centerline velocity decay rate
$\bar{U}$ = mean velocity
U_m = jet centerline mean velocity
U_0 = jet velocity at nozzle exit
X = axial distance from nozzle exit plane
Y = transverse coordinate
θ = shear-layer momentum thickness

Introduction

THE influence of sound upon jets has been observed since at least 1858, when John Leconte[1] noticed gas lamp flames pulsating in synchronization to music of Beethoven being performed on a violoncello. To Leconte, the phenomenon was purely an intellectual curiosity. Since that time, the growth of technology has made the phenomenon a subject of considerable practical interest, particularly in relation to jet propulsion and fluidics.

Leconte's observations were of laminar jets in which transition was precipitated by appropriate sounds. Modern studies also have considered the effect of sound on turbulent jets and mixing layers. Such flows begin with an instability process which grows and leads to a breakdown to fully turbulent flow which, in turn, continues to develop toward a final state in which the mean and turbulent properties are self-preserving. The region in which self-preservation, or at least self-similarity, is approached will be referred to here as the main region and that preceding it as the initial region. Acoustic effects in the initial region have been considered in studies of shear-layer instability, of large-scale orderly structures, and of jet noise. Main region studies often have been concerned with fluidic amplifier applications.

Free shear-layer instability studies, such as those of Browand,[2] Freymuth,[3] and Miksad,[4] have employed acoustic forcing to control the instability frequency in measurements of the dependence of disturbance amplification rate upon frequency. The control of the instability frequency is observed as a sharpening of the peaks of the turbulent energy spectra of the shear-layer flow.

The final stages of the instability process have been examined in studies of large-scale orderly structures. Crow and Champagne[5] and Hussain and Zaman[6] found structures in round jets in the form of toroidal vortices. The structures were strengthened by acoustic forcing, which was observed to increase entrainment and jet width in the initial region and the beginning of the main region.

Bechert and Pfizenmaier[7] and Moore[8] have reported that the broadband noise radiated by round jets may be increased by pure tone acoustic forcing. Kibens[9] found that appropriate frequency acoustical forcing of a round jet organized the large-scale structures, resulting in far-field acoustic spectra dominated by discrete peaks. While the overall sound pressure level was increased, the broadband component decreased. He also presented a hypothesis for the strength of the interaction between the shear-layer instability and the large-scale structure frequencies, thus providing a comprehensive view of acoustic disturbance phenomena in the initial region.

Most studies of acoustic effects upon the flow in the main region have been motivated by practical considerations such as determining the frequencies which produce the largest effects upon fluidic amplifiers. Quantitative measurement of these effects have been made by Vlasov and Ginevskii,[10] Becker and Massaro,[11] Roffman and Toda,[12] Goldschmidt and Kaiser,[13] and others surveyed by Rockwell.[14] These studies report that certain frequencies increase the velocity profile width and decrease the centerline velocity at certain locations in turbulent jets. However, none of these studies present results that are sufficient to describe adequately the overall effects upon the jet or to illuminate the mechanism producing the effects.

Various proposals for the interaction mechanism linking the acoustic field and the flowfield effects have been advanced. Simcox[15] proposed a direct acoustic-turbulent interaction throughout the jet. Morkovin and Paranjape's [16] research suggested to them that the sound field's oscillation of the leaving stagnation point on the nozzle provided the interaction. Other mechanisms proposed included flapping of the jet and effects upon the turbulent-nonturbulent interface. The results now presented are from the first part of a study which was undertaken to determine the interaction mechanism responsible for changes in the mean flow in the main region of the jet. The study included measurements of mean pressure profiles, turbulence intensities, Reynolds stresses, and turbulent energy spectra in the initial and main

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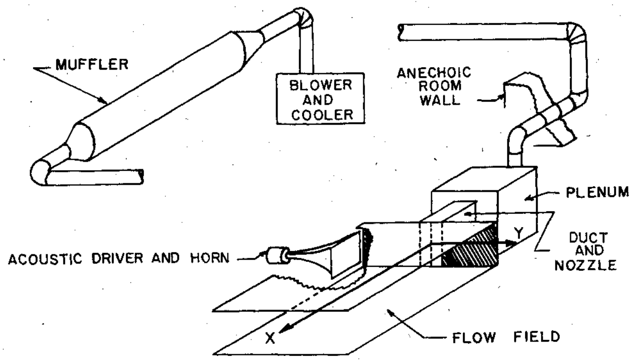

Fig. 1 Schematic diagram of experimental facility.

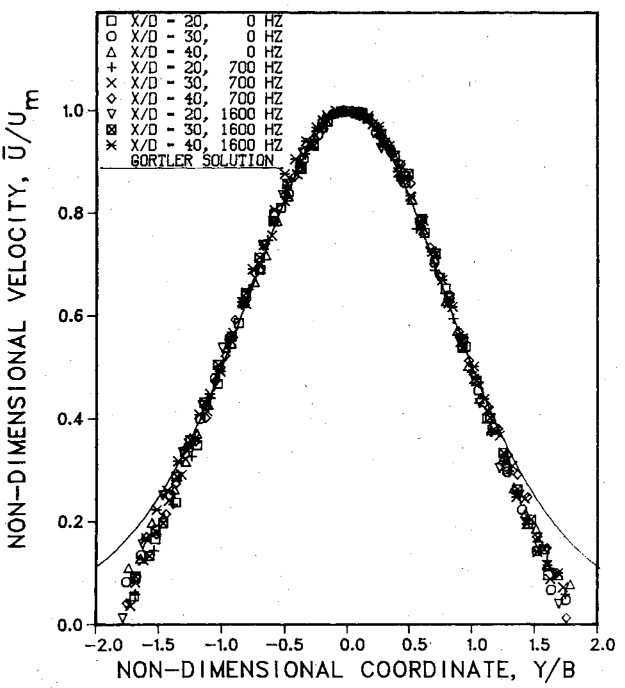

Fig. 2 Nondimensional mean velocity profiles.

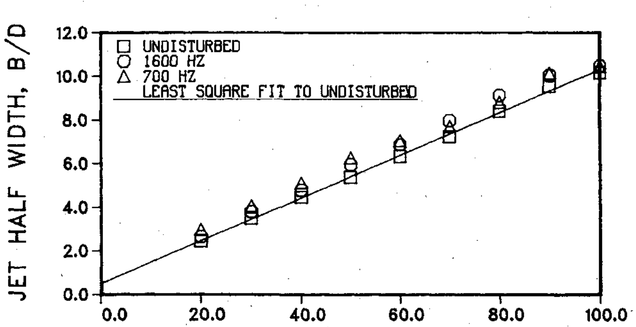

Fig. 3 Jet half-width growth with and without disturbance.

regions. The complete results are reported by Chambers[17] and those presented here are limited to the effects of acoustic disturbances upon the mean flow parameters in the main region. The results of the turbulence measurements and conclusions about the interaction mechanism are to be presented in a future paper.

Apparatus and Instrumentation

A schematic diagram of the experimental apparatus is shown in Fig. 1. A nozzle with exit dimensions of 6.35×305 mm was operated at a Reynolds number based upon nozzle width and exit mean velocity of approximately 6000. The flowfield was located inside an anechoic room with inside dimensions of 3.7×3.7×3.7 m. The entrained flow was constrained by acoustically absorbent walls in the nozzle exit plane. The two-dimensional character of the flowfield was preserved by two horizontal steel walls of 0.91×1.52 m. The flowfield was found to exhibit vertical uniformity over the central 85% of the distance between confining plates.

The air flow was provided by a centrifugal blower located in a concrete block enclosure more than 9 m from the anechoic room. The air from the blower was cooled to ambient temperature, passed through a 6.1-m-long annular fiberglass-lined muffler, ducted through the anechoic room wall, and passed through a baffled fiberglass-lined plenum before entering a 102×305-mm duct leading to the nozzle. The duct contained a honeycomb flow straightener and screens. Special precautions were taken to provide the duct with sufficient acoustic absorption and stiffness to minimize internal sound and vibration levels. The duct ended in a nozzle with a smooth 16 to 1 contraction. These steps taken to provide a quiet, low turbulence flow were sufficient to produce a turbulence intensity at the mouth of the jet that in all cases was under 0.5%.

An acoustic driver and rectangular section exponential horn applied a transverse acoustic field outside the nozzle. The system was used over a frequency range of 200-4200 Hz at a sound pressure level of 105 dB SPL re 20 μPa at the monitoring microphone. The microphone was operated in a feedback loop to maintain the sound pressure level it sensed constant to within 0.3 dB. The sound field produced by two frequencies was surveyed between the nozzle mouth and 80 nozzle widths downstream and found to vary smoothly over a range of less than 7 dB. No evidence of significant standing wave or nozzle resonance phenomena was observed.

Flowfield mean total pressure profiles were obtained using two pitot tubes mounted on a motorized traversing system and connected to differential pressure transducers. The two transducer outputs were processed with 1 s time constants and plotted simultaneously on an X-Y-Y recorder vs a signal proportional to position obtained from a traversing system potentiometer. The jet was traversed at a speed of 0.28 mm/s. The measured total pressures were converted to mean velocities directly using no correction for turbulent fluctuations and assuming mean static pressure was ambient.

Experimental Results

The mean velocity profiles in the main region of undisturbed turbulent plane jets display similarity when scaled by the local centerline mean velocity, and the profile half-width. Additional conditions of main region similarity for plane jets involve velocity profile half-width and centerline velocity decay

$$B/D=K_1[(X/D)-C_1] \tag{1}$$

and

$$(U_m/U_0)^{-2}=K_2[(X/D)-C_2] \tag{2}$$

Disturbed and undisturbed case mean velocity profiles measured at three distances from the nozzle are shown in Fig. 2. It may be observed that all cases exhibit similarity and agreement with Görtler's[18] solution. Defining a Strouhal number based upon nozzle width and jet exit velocity, the two frequencies used corresponded to Strouhal numbers of 0.30 and 0.69.

Jet half-widths obtained from measured mean total pressure profiles for the undisturbed case and for disturbance Strouhal numbers of 0.30 and 0.69 are presented in Fig. 3. The disturbed cases exhibit faster widening than the undisturbed case in the region within approximately 60 slot widths from the nozzle, but thereafter appear to show decreases in widening rate toward that of the undisturbed case. Note that the accuracy of this data decreases with distance from the nozzle as velocities and pressures decrease and become more susceptible to the effects of drafts. It is important to note that the widening rates actually are increased by the disturbance, and that the larger half-widths are not simply the results of shifts in the virtual origins caused by flow changes in the initial region. To determine whether the decrease of widening rate beyond $X/D = 60$ resulted from increasing distance from the sound source, one set of data was taken with the sound source moved 50 nozzle widths downstream. This move did not increase the widening rate in the region beyond $X/D = 60$. Thus, the greater widening rate does not appear to be fundamentally a function of proximity to the sound source.

It may be concluded that disturbances at these two frequencies initially produce widening rates greater than that of the undisturbed jet, but that by approximately 80 nozzle widths downstream, the rates decrease to nearly the undisturbed rate. Measurements of turbulent properties reported by Chambers[17] revealed corresponding behavior at these frequencies.

The two frequencies employed produced increases in widening rate only at the beginning of the main region. The frequency dependence of the mean flow effects produced in this region was investigated for Strouhal numbers ranging from 0.1 to 1.8. The widening rate, velocity decay rate, and virtual origins were determined from least square fits to half-widths and centerline mean pressures measured with the traversing pitot tube system. Initial measurements revealed very small effects at Strouhal numbers greater than 1.08. Final measurements were limited to frequencies below a Strouhal number of one, and were obtained using pressure profiles at 20, 25, 30, 40, 45, and 50 nozzle widths from the exit plane. Typical half-width and velocity decay ratio results are shown in Fig. 4.

The widening rates, geometric origins, velocity decay rates, and velocity origins obtained from such plots are presented as functions of Strouhal number in Figs. 5, 6, 7, and 8, respectively. The undisturbed case values are plotted at zero Strouhal number. It may be observed that appropriate frequencies of the applied sound increased the widening rate up to 25% above the undisturbed case. The increases are most noticeable for Strouhal numbers below 0.4. The widening rates between Strouhal numbers of 0.4 and 0.62 exhibit considerable scatter. Further discussion of this apparent scatter is appropriate.

During the course of the experiments, it was observed that in this disturbance frequency range, the measured pressures slowly underwent large fluctuations in "mean" level. The phenomenon was studied in detail at the frequency exhibiting the most violent fluctuations, a Strouhal number of 0.47. It may be noted that this frequency is nearly twice the natural frequency of the shear-layer instability. Histograms of the velocity on the jet centerline 50 slot widths from the nozzle measured with a hot-wire anemometer and further measurements employing an additional hot wire in the shear layer revealed that the flow was alternating randomly between two modes of response to the disturbing sound. One mode exhibited a lower centerline velocity and a greater half-width than the other. Thus, the scattered mean flow results in this frequency range may be interpreted as very roughly defining upper and lower bounds of the response.

The geometric origin appears to be less affected by the applied sound than the widening rate. All of the geometric origins are negative; that is, the jet appeared to widen from zero width upstream of the nozzle mouth. The geometric origin tended to move upstream when affected by the applied sound, although at the Strouhal numbers corresponding to the largest widening rates, the trend is the opposite with slight downstream shifts. These results exhibit more scatter than the widening rates, but this is expected from geometric considerations. A widening rate change of 2% for a fixed half-width at $X/D = 20$ will result in roughly a 10% change in the geometric origin assuming typical conditions. The geometric origin results correspondingly show very large scatter in the region of the intermittent fluctuations.

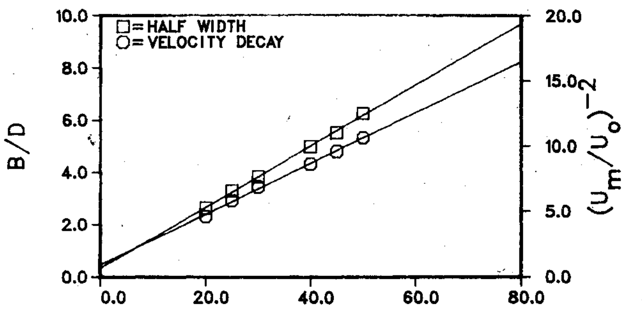

Fig. 4 Typical half-width and velocity decay results.

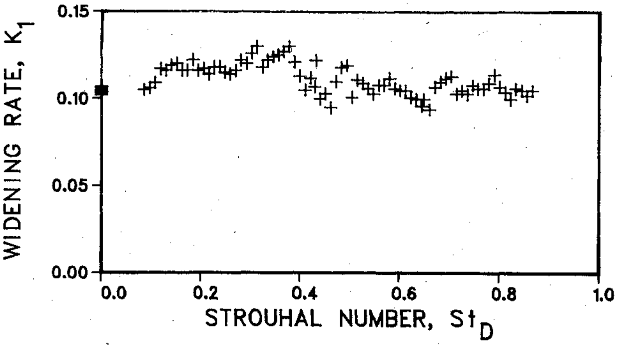

Fig. 5 Strouhal number dependence of widening rate.

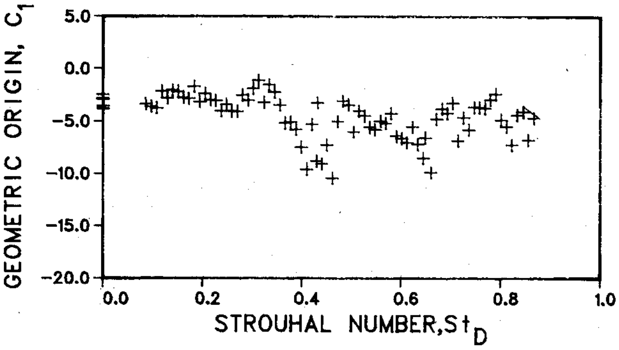

Fig. 6 Strouhal number dependence of geometric origin.

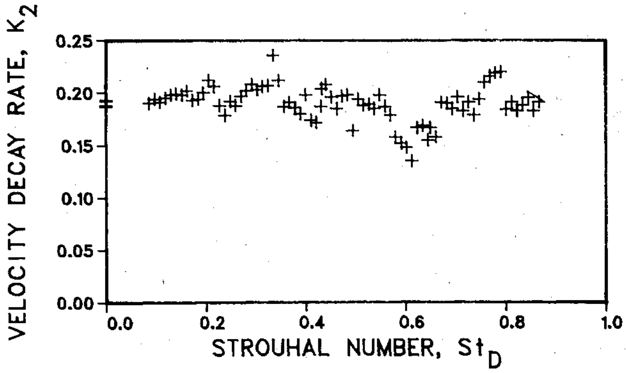

Fig. 7 Strouhal number dependence of velocity decay rate.

The velocity decay results are similar to the widening rate results in terms of regions of scatter, of good repeatability, and of little apparent effect, but they also differ in showing many more cases of significant decreases.

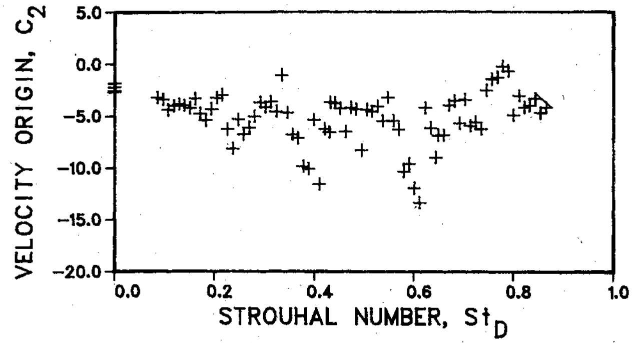

Fig. 8 Strouhal number dependence of velocity origin.

As in the case of the geometric origins, the majority of the changes in the velocity origins appear to be in the upstream direction, while the largest decay rates appear to be accompanied by small downstream shifts. The magnitude range and the apparent scatter are larger for the velocity origin results than for the geometric origins, but like them, all are negative.

The scatter in the results may be attributed to three major sources. One source is measurement inaccuracies. It is estimated that the centerline mean pressures and the half-widths were measured to an accuracy of approximately ±4.5%. Assuming the worst possible distribution of these errors, the widening and decay rates could vary ±10%. A good check on this estimate is provided by the undisturbed case results. All undisturbed widening rates fall within ±4.5% of their average value, while the velocity decay rates are within ±6%, except for one point at ±8.5%. The decay rate results may be expected to be less accurate, for they depend upon the absolute calibration of the pressure transducer, while the widening rates depend only upon its linearity. The sensitivity of the origins to changes in the two rates was discussed previously.

The second source of scatter may be related to the nature of the phenomenon. The experimental apparatus was periodically removed and returned to the anechoic room, with the flowfield separated from the acoustic source. The subsequent realignment of the source with the flowfield may have resulted in small changes in the disturbing sound field. The literature, such as Hussain and Zaman[6] and Morkovin and Parajape,[16] and other results of this study suggest that the effects are dependent upon sound level and perhaps local spatial gradients of the level. Thus, such small changes in the sound field could result in changes in the effect on the flowfield which are apparent as scatter. The third source of scatter is the large fluctuation phenomenon discussed previously.

Despite the scatter, the frequency dependence results show that in the region from $X/D=20$ to 50, the appropriate frequency and sound pressure level can produce large changes in the mean flow widening and velocity decay as well as the virtual origins.

Comparison of Results to Earlier Works

Frequency Dependence

The measured frequency dependence of effects in the main region of the jet can be compared with various sensitive or natural frequencies reported in the literature which may be grouped into three categories. The first category includes frequencies determined through studies of disturbed jets and mixing layers. Generally, the frequencies in this category were determined through studies of gross changes in the mean flow resulting from acoustical or vibrational disturbance of the flow. The second category contains the frequencies found to exhibit maximum growth in experimental and theoretical studies of shear-layer instability. The third category contains frequencies determined in studies of large-scale orderly structures.

The comparison of the measured frequency dependence to the reported frequencies is complicated by the different characteristic lengths used in Reynolds and Strouhal numbers. The centerline mean velocity at the mouth of the jet U_0 is employed nearly universally as the characteristic velocity. However, the nozzle slot width D and the shear layer momentum thickness θ are used alternatively as characteristic lengths. The momentum thickness is defined as

$$\theta=\int_0^\infty \frac{\bar U}{U_m}\left(1-\frac{\bar U}{U_m}\right)\mathrm{d}y \tag{3}$$

The instability literature suggests that the momentum thickness is most characteristic of the linear instability region in mixing layers and in jets so long as it is much smaller than the jet width or diameter. In the present study, hot-wire anemometer measurements of the initial "top-hat" mean velocity profile revealed that to within 3%, $D/\theta=63.3$ for the undisturbed jet and the jet disturbed at $St_D=0.30$ and 0.69. Hot-wire measurements of the nozzle boundary-layer mean velocity profiles approximately one half-nozzle width upstream of the exit showed that the three cases had virtually identical scaled laminar velocity profiles with momentum thicknesses differing by less than 4%. Turbulence intensities measured at the jet centerline in the exit plane also exhibited insignificant differences, all being less than 0.5%, with major contributions appearing to be made by electronic noise. The two disturbance frequencies employed in these measurements did produce significant changes in the main region flow. It is assumed that in the present study, all cases had laminar nozzle boundary layers and nearly constant initial shear-layer momentum thickness. Hence, nozzle width Strouhal numbers are assumed directly proportional to shear-layer momentum thickness Strouhal numbers for this study, being larger by the factor D/θ. Results are presented as nozzle width Strouhal number.

Sensitive and natural frequencies reported in the literature are compared to the present results in Table 1. The procedure used in compiling Table 1 was to use results in the literature to calculate expected sensitive or natural frequencies for the jet of the present study, expressing the results in terms of a nozzle width Strouhal number wherever possible. Results presented as Strouhal and Reynolds numbers based upon nozzle width or diameter are compared directly. In those cases in which the Strouhal number is presented as a function of Reynolds number, the Reynolds number of this study, 6000, is used. Results in the literature based solely upon momentum thickness are converted to numbers based upon the current nozzle width by multiplying by 63.3, the assumed D/θ for the current study. In the case of Strouhal numbers reported in terms of both momentum thickness and nozzle width, both numbers are presented in the table; the width-based number directly and the momentum-thickness number converted by multiplication by 63.3, D/θ of the current study. These conversions to nozzle width Strouhal numbers are perfomed only to simplify comparisons to the present results, and are not based upon any assumption that the width Strouhal number is more appropriate than the momentum-thickness number.

Study of the tabulated Strouhal numbers reveals that most appear to fall within roughly three numerical groups. These groups might be considered to be under 0.45, between 0.5 and 0.65, and between 0.9 and 1.2. The present study shows the greatest effects upon the widening rate at Strouhal numbers between 0.3 and 0.4. The natural frequency of the present jet corresponds to a Strouhal number of 0.24 as determined from measurement of the undisturbed shear-layer velocity fluctuation spectrum at $X/D=0.25$ $(X/\theta=16)$. It may be noted that disturbance at this frequency was not the most effective.

Mixing layers, round jets, and plane jets with laminar or turbulent nozzle boundary layers and top hat or developed initial velocity profiles are included in the conditions of the

Table 1 Reported free shear flow natural and sensitive frequencies

Reference and description	Reynolds number $Re_D = U_0D/\nu$, $Re_\theta = U_0\theta/\nu$ or as indicated	Reported Strouhal number $St_D = FD/U_0$, $St_\theta = F\theta/U_0$ or as indicated	Predicted Strouhal number $St_D = FD/U_0$
Present study Natural frequency	6000 or $Re_\theta = 95$	$St_D = 0.24$ or $St_\theta = 0.0038$	0.24
Present study Jet widening Sensitive frequency	6000 or $Re_\theta = 95$	$St_D = 0.38$ or $St_\theta = 0.0060$	0.38
Winant and Browand[23] and Browand and Weidman[34] Experimental mixing layer	$Re_h = \Delta Uh/\nu = 300$ $h = \Delta U/(\mathrm{d}U/\mathrm{d}y)_{\max}$	$St_h = fh/U = 0.19$	3.04
Browand[2] Experimental mixing layer instability	$Re_\theta = 230$	$4\pi\theta f/U = 0.227$	1.14
Freymuth[3] Experimental mixing layer instability	$42 < Re_\theta < 334$	$St_\theta = 0.017$	1.08
Michalke[19]	Inviscid theory	$St_\theta = 0.0167$	1.05
Miksad[4] Experimental mixing layer instability	$Re_\theta = 150$	$4\pi\theta f/U = 0.2175$	1.10
Spatial instability theory	Inviscid theory	$4\pi\theta f/U = 0.2216$	1.12
Becker and Massaro[11] Experimental disturbed round jet	600-20,000	$St_D = 0.012\sqrt{Re_D}$	0.93
Rockwell[21] and Rockwell and Niccolls[22] Experimental plane jet	1860-10,800	$St_D = 0.012\sqrt{Re_D}$	0.93
Sato[20] Experimental plane jet instability, symmetric mode	1500-8000 or $100 < Re_\theta < 400$	$St_D = 0.23$ or $St_\theta = 0.015$	0.95
Beavers and Wilson[35] Experimental round jet	500-3000	$St_D = 0.63$	0.63
Lau and Fisher[36] Experimental round jet	62,000	$St_D = 0.52$	0.52
Mattingly and Criminale[7] Viscous nonlinear instability theory	600	$St_D = 0.55$	0.55
Rockwell[14] Round jet survey	6000	$St_D = 0.52\text{-}1.3$	0.52-1.3
Rockwell and Toda[31] Experimental disturbed attached plane jet	700-5000	$St_D = 0.009\sqrt{Re_D}$	0.70
Sato[20] Experimental plane jet instability, antisymmetric mode	1500-8000 or $100 < Re_\theta < 400$	$St_D = 0.14$ or $St_\theta = 0.0092$	0.58
Thompson[33] Experimental disturbed plane jet Maximum centerline disturbance growth	26,700	$St_D = 0.18$ or $St_\theta = 0.0093$	0.59
Wille[38] Plane jet inviscid instability theory	Inviscid theory	$f\delta^*/U_0 = 0.0232$ (δ^* = boundary layer displacement thickness)	0.53
Beavers and Wilson[35] Experimental plane jet	500-3000	$St_D = 0.43$	0.43
Crow and Champagne[5] Experimental disturbed round jet	$> 10{,}000$	$St_D = 0.3$	0.3
Hussain and Zaman[6] Experimental disturbed round jet	11,000-113,000	$St_D = 0.3$ (Tripped nozzle boundary layer) $St_D = 0.4$ (Untripped)	0.3 0.4
Kaiser[32] Experimental disturbed plane jet	4500 5150 6000	$St_D = 0.38$ $St_D = 0.37$ $St_D = 0.42$	0.38 0.37 0.42
Michalke[39] Inviscid instability theory for round jet at $X/D = 2$	$D/\theta = 12.5$	$St_D = 0.35$	0.35
Rockwell[14] Plane jet survey	6000	$St_D = 0.15\text{-}0.65$	0.15-0.65
Roffman and Toda[12] Experimental disturbed plane jet	200-4300	$St_D = 0.14$	0.14
Thompson[33] Experimental disturbed plane jet Maximum shear layer disturbance growth	11,000	$St_D = 0.45$ or $St_\theta = 0.0061$	0.39
Vlasov and Ginevskii[10] Experimental disturbed round jet	30,000-260,000	$St_D = 0.33\text{-}0.54$	0.33-0.54
Wille[38] Experimental disturbed plane jet instability	$> 15{,}000$	$f\delta^*/U_0 = 0.0161$ (δ^* = boundary-layer displacement thickness)	0.37
Wooldridge et al.[40] Experimental round jet	26,000-60,000	$St_D = 0.4\text{-}0.5$	0.4-0.5

studies surveyed. The present study had laminar nozzle boundary layers and a top hat initial velocity profile. The initial shear-layer velocity profile of the present study compares well to the hyperbolic tangent profile of the shear layer instability studies of Michalke,[19] Freymuth,[3] Browand,[2] and Miksad.[4] These studies, and the plane jet studies of Sato,[20] Rockwell,[21] and Rockwell and Niccolls[22] all report Strouhal numbers in the region between 0.9 and 1.2.

Round and plane jet studies make up the two lower frequency groups. All studies of large-scale structures in round jets fall within the lowest group. The results of these investigations of large-scale structures suggest a possible explanation for the groupings.

The groups very roughly correspond to one, two, and four times a Strouhal number of 0.3. Such multiples could result from vortex coalescence beginning at frequencies in the highest group. Winant and Browand[23] have documented the phenomenon through which two or more vortices merge and produce subharmonics. Crow and Champagne[5] describe violent subharmonic formation in the case when their round jet was forced at a Strouhal number of 0.6. The intermittent fluctuation phenomenon believed responsible for the frequency region of large scatter in the present study was strongest at a disturbing frequency of twice the natural shear-layer frequency. Hot-wire traces in the shear layer revealed that the fluctuations corresponded to the appearance and disappearance of the second subharmonic of the disturbing frequency. Kibens[9] found that acoustic forcing was most effective in a round jet when the frequency of the large-scale structures was the third subharmonic of the forcing frequency. In turn, this forcing frequency was very close to the undisturbed shear-layer instability frequency. He noted that his observed frequencies probably resulted from a process in which neither the shear layer nor the large-scale structure frequencies were at their independent undisturbed case values, but had adjusted to values for which subharmonic matching was optimal. It might be expected that in cases of different shear-layer thickness and instability frequency, the large-scale structure frequency might occur at a subharmonic other than the third. Kibens[9] also explains that this matching process is the likely reason for differences in observed frequencies for the large-scale structure. This reasoning is supported by Hussain and Zaman's[6] finding that large-scale structure in a round jet occurred at a Strouhal number of 0.3 when the nozzle boundary layer was tripped, and 0.4 when laminar.

These round jet results of Kibens[9] and of Hussain and Zaman[6] offer some explanations for the groups of frequencies reported and for the variations within the groups. Hypotheses about large-scale structures in round jets cannot, however, be applied to plane jets without caution. In round jets, such structures take the form of toroidal vortices, while in plane jets, two independent shear layers may grow in either symmetric or asymmetric modes before merging at the end of the potential core. Coherent large-scale structures have not been identified formally in plane jets, although mixing layer studies such as that of Winant and Browand[23] and plane jet flow visualization by Rockwell and Niccolls[22] certainly suggest their presence. The slight suggestion of harmonics (increased widening rates between Strouhal numbers of 0.3-0.4 and also between 0.6-0.8) might be interpreted as a very weak indication of vortex coalescence phenomena.

Round jet studies do offer some rather tenuous explanations for the relatively low frequencies observed to cause the largest mean flow changes in the present study. The role of pressure fluctuations generated near the end of the potential core in round jets has been the subject of some dispute in interpreting hot-wire anemometer measurements within the potential core, as discussed by Ko and Davies.[24] Kibens[9] notes that centerline velocity fluctuations are induced upstream of the locations at which large-scale structures are formed in the shear layer in his round jet study. Perhaps a feedback of such low frequencies controls the near-nozzle shear-layer behavior in the present study. However, subharmonics of the disturbing frequency were also observed. Moore[8] reports observations of large-scale structures within one half-diameter of the nozzle in his round jet study.

Mean Flow Results

Table 2 compares the jet mean flow properties of this study with others reported in the literature. Various explanations have been offered for differences in these parameters. Kotsovinos[25] has proposed that such variations are a result of changes in widening rate with distance from the nozzle and Bradshaw[26] suggests that these changes are caused by self-induced drafts. The results of the present study do not support Kotsovinos' contentions. Many authors have attributed these mean flow variations to different flow conditions upstream of the nozzle mouth. Flora and Goldschmidt[27] performed a study which showed that different upstream turbulence intensities result in different mean flow development. Hussain and Clark[28] and Hill et al.[29] have shown that changes in the nozzle boundary layers also affect the main region mean and turbulent flows. Gutmark and Wygnanski[30] note that all jets may not even approach the same asymptotic self-preserving state. The results of the present study show large variations may be produced by acoustic disturbance.

Rockwell's[14] survey of disturbed jets revealed that the most common mean flow effects of disturbance near the most sensitive frequency are increases in the velocity profile width and decreases in the centerline velocity. Such effects can result from various combinations of changes in the virtual origins, the widening rate, and the decay rate.

In the present study, the tendencies were for the geometric and velocity origins to shift upstream, and the widening rate to increase when the jet was disturbed near the most sensitive frequency. These changes resulted in disturbed mean velocity profiles similar to those described in Rockwell's[14] survey, and reported by Refs. 5, 6, 10-12, and 31-33. The results of the present study also show little effects on the main region mean flow at frequencies three to four times the natural frequency, in agreement with Rockwell's[21] findings for the initial region.

Disturbance frequencies between the most sensitive frequency and this upper zone were found by Rockwell[21] to lengthen the potential core, behavior which might be expected to result in downstream shifts of the virtual origins. The present data did suggest downstream shifts of the velocity origins near $St_D = 0.8$. These shifts could also produce narrower velocity profiles in the main region of the jet, as found by Rockwell[21] and by Vlasov and Ginevskii.[10] Profile narrowing could also be indicated by decreases in widening rate, but the present study shows only very small decreases in this frequency region. The meager evidence of potential core lengthening in the results of the present study might be attributed to different vortex structures. Rockwell's[21] jet exhibited symmetric vortex modes, while those of the present study appeared asymmetric. The modal behavior of the present study was not determined very adequately, but it is useful to consider the results of such a difference. Photographs in Rockwell's paper suggest that the asymmetric modes produce greater lateral distortion of the flow in the initial regions than do the symmetric modes. Thus, symmetric modes appear more likely to maintain the potential core.

Disturbance frequencies less than one-third the most sensitive frequency were observed by Rockwell[21] to widen mean velocity profiles. The present study included only a few frequencies in this region, and the lowest of them do not exhibit appreciable changes in widening rate or geometric origin, the parameters controlling the profile width.

The differences between the observed results and those surveyed in the literature may be attributed to several sources. As discussed previously, the initial conditions of the flow play a role in the flow development. These conditions also appear to play an important role in the effects of disturbances upon

Table 2 Reported mean flow properties of turbulent plane jets

Reference and comments	Reynolds number, Re_D	Widening rate, K_1	Decay rate, K_2	Geometric origin, C_1	Velocity origin, C_2
Present study (ranges produced by acoustic disturbances in cases of six measured pressure profiles)	6.0×10^3	0.094-0.130	0.136-0.236	−10.4- −1.1	−13.4- −0.3
Ajagu[41]	1.6×10^4	0.092	0.82	−0.7	3.30
Cervantes[42]	1.0×10^4	0.083	0.24	−6.62	4.53
Everitt and Robins[43] (varying aspect ratio nozzles)	$1.6\text{-}7.5\times 10^4$	0.09-0.11	0.14-0.22	—	—
Flora and Goldschmidt[27] (different nozzles and initial turbulent intensities)	$2\text{-}3\times 10^4$	0.109-0.130	0.158-0.227	−15.0	2.0
Gutmark and Wygnanski[30]	3×10^4	0.1	0.19	−2	4.7
van der Hegge Zijen[44]	1.33×10^4	0.100	0.205	0	−1.70
Heskestad[45]	2.5×10^4	0.113	0.364	5.3	5.3
Hussain and Clark[28] [a) top hat and b) developed initial mean velocity profiles]	3.26×10^4	a) 0.1183 b) 0.1154	0.1227 0.1793	−2.15 2.17	−4.47 0.63
	8.14×10^4	a) 0.1195 b) 0.1101	0.1132 0.1893	1.90 2.60	−2.11 1.73
Jenkins[46] (jet at different temperatures above ambient)	1.45×10^4	0.088-0.096	0.160	−4.5- −2.5	4.0
Kaiser[32] (ranges produced by acoustic disturbance)	$4.5\text{-}6.0\times 10^3$	0.100-0.128	0.187-0.260	−4.6-1.2	0.0
Miller and Comings[47]	1.78×10^4	0.0983	0.227	−1.572	−1.572
Mulej[48]	1.6×10^4	0.095	0.185	−0.789	13.2
Ott[49]	1×10^4	0.0968	0.228	−3.0	7.0
Young[50]	1×10^4	0.0875	0.150	8.75	−1.25

the jet. In the present study, various devices such as screens and boundary-layer trips were placed upstream of the jet nozzle and found to alter greatly the sensitivity of the jet. Increases in initial turbulence intensity were found to decrease sensitivity. Jet Reynolds number effects, which were observed in the present study, might also be classed as initial condition effects.

Other factors which may affect the sensitivity of the jet are low level background noise and vibrations. The present study was conducted in an anechoic room isolated from building vibrations by a separate foundation, and, hence, may be considered to be very well isolated with low background noise and vibration levels. Other reviewed studies did appear to take care to reduce background noise and vibration levels, but it appears likely that their levels were somewhat higher.

Another contributor to differences in results may be the ways in which the jets were disturbed. The various methods may be assumed to result in different spatial distributions of the disturbance levels, and corresponding differences in symmetry. Morkovin and Paranjape's[16] study led them to conclude that the spatial pressure gradient at the nozzle lip is the parameter truly representative of the effective disturbance level. The role of the disturbance level is discussed by Rockwell,[14] Rockwell and Toda,[31] and Hussain and Zaman.[6] It has been reported, and confirmed in the present study of intermittent fluctuations, that the effect may exhibit both a threshold and a saturation disturbance level. If these levels are frequency dependent, in the present study, in which the disturbance level was held constant, various frequencies may have been disturbed at levels ranging from below their threshold to above their saturation level. Thus, comparisons of studies, each with its own spatial disturbance distribution and disturbance level, would appear likely to be characterized by less than perfect agreement.

Conclusions

The purpose of this study was to examine the interaction between an acoustic field and a turbulent plane jet. In particular, the effects on the mean flow are reported. The following conclusions have resulted.

1) Acoustic fields of a wide frequency range produce changes in the mean flow of a jet extending well into the main region.

2) These changes in the flow decrease at larger distances from the nozzle.

3) The behavior of the flow at the beginning of the main region is related to changes in the flow in the initial region.

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