Asymmetric forcing of a turbulent rectangular jet with a piezoelectric actuator

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(Received 6 June 2000; accepted 25 January 2001)

A moving wall section attached to a piezoelectric actuator was used to perturb the airflow exiting a fully developed turbulent channel. The Reynolds number based on the channel width and centerline velocity was 4240. The maximum velocity of the moving wall section was 9.5 cm/s (2.3\% of the mean centerline velocity), and the maximum displacement was 120 microns, corresponding to 1.84 wall units. The actuator frequency and displacement amplitude were tuned independently to generate different effects on the flow, and both quantities were documented to provide precise boundary conditions for numerical codes. Hot-wire measurements showed that actuation affects both the mean and rms velocity profiles downstream of the channel exit. In all cases, forcing yields mean profiles that are symmetric with respect to the centerline. However, forcing at low frequencies \((St \leq 0.30)\) causes faster decay of the centerline velocity, higher spreading rates in the far field, and asymmetric rms profiles compared with unforced flow. The maximum rms value crosses from the actuator side to the nonactuator side as the flow moves downstream. This behavior is thought to be caused by staggered but asymmetric vortical structures developing in the opposing shear layers. Forcing from \(St = 0.39\) through \(1.46\) leads to altered but symmetric rms profiles and spectra compared with unforced flow. Forcing in the range \(St < 0.50\) yields centerline rms values that initially are larger than, but further downstream smaller than in the unforced flow. © 2001 American Institute of Physics. [DOI: 10.1063/1.1357817]

I. INTRODUCTION

Over the last three decades, the amount of research on control of single-phase flows has been significant. According to Gad-el-Hak,\textsuperscript{1} the idea of flow control was originated by Prandtl (1904), who introduced boundary layer theory, explained the physics of separation involved, and demonstrated experiments in which a boundary layer could be controlled. Over the last decades, we have experienced a wide variety of control methods, both passive and active. Active control schemes refer to methods that add energy to the flow, while passive methods do not. Active methods can be used intermittently and tuned in real time, while passive methods usually involve fixed alterations in geometry, and hence are limited to steady configurations.

Much effort has been devoted to investigating the flow of rectangular jets. Examples of the numerous studies on incompressible jets include the work of Sforza \textit{et al.},\textsuperscript{2} Trenchato and Sforza,\textsuperscript{3} and Sfeir\textsuperscript{4,5} on jets from sharp-edged orifices, Heskestad\textsuperscript{6} and Sfeir\textsuperscript{4,5} on jets exiting long rectangular channels, and Gutmark and Wygnanski\textsuperscript{7} and Krothapalli \textit{et al.}\textsuperscript{8} on jets exiting contractions. These studies showed that jets exhibit a self-preserving region in the far field characterized by a quadratic decay of the mean centerline velocity, a linear growth of its spreading, and constant values of centerline turbulence intensities when normalized by the local mean centerline velocity.

In the near field of rectangular jets, large-scale coherent structures have been detected and examined by a number of researchers. Both symmetric and antisymmetric modes of instabilities have been identified in the initial region of the shear layer. The type of mode depended on the shape of the jet exit velocity profile\textsuperscript{9} and the downstream location.\textsuperscript{10} Antonia \textit{et al.}\textsuperscript{11} and Thomas and Prakash\textsuperscript{12} found that the near field is dominated by large-scale, symmetric structures. The symmetric alignment of instabilities was associated with top-hat shaped mean velocity profiles at the exit of the nozzle. Further downstream, in the fully developed region of the jet, the existence of antisymmetric structures has been described by a number of researchers.\textsuperscript{11,13–15}

In light of the many practical applications of rectangular jets, numerous attempts have been made to control mixing and entrainment by manipulating the natural development of coherent structures in the jet near field. Active control schemes have been used extensively to alter the flow structure.\textsuperscript{1} Typically these schemes are open loop, and the control strategy is predetermined.

Examples of active control methods include acoustic excitation, deflection of flexible walls or tabs, and oscillations of rigid walls. Acoustic excitation, applied by Crow and Champagne\textsuperscript{16} to study the preferred frequency of a circular jet, has become a common manipulation technique. In the experiments described below, acoustic speakers were implemented to perturb the initial shear layer of rectangular or
plane jets. Hussain and Thompson\textsuperscript{17} studied the near field of a plane jet subjected to sinusoidal acoustic perturbations. They found that the induced symmetric modes remained symmetric as they propagated downstream. Also, Zaman and Hussain\textsuperscript{18} demonstrated that the turbulence intensities in the near field of an acoustically forced plane jet were suppressed compared with the values in the unforced case. Thomas and Goldschmidt\textsuperscript{15} and Farrington and Claunch\textsuperscript{19,20} applied acoustic forcing to increase spreading and mixing in planar jets. The observed increases were attributed to larger vortical structures induced in the shear layers by the forcing. Rajagopalan and Ko\textsuperscript{21} studied the near field of a plane jet subjected to excitation at two frequencies corresponding to the shear layer mode and the preferred mode. Most recently, Huang and Hsiao\textsuperscript{22} used earphones on both sides of a plane jet to acoustically excite the fundamental frequency in either symmetric or antisymmetric modes. In all of the above forcing studies, the jets typically initiated downstream of a contraction. Thus, the initial mean velocity profiles were top-hat shaped with thin shear layers, and initial turbulence levels in the jet cores were small or negligible.

The recent work of Wiltse and Glezer\textsuperscript{23,24} on square jets differs from the above control studies in that the jets emanated from a relatively long duct with constant cross section, and the flow exiting the duct was turbulent. In these experiments, piezoelectric actuators in the form of cantilevered plates were located immediately downstream of the jet exit and oriented to generate streamwise velocity fluctuations. In the earlier experiments,\textsuperscript{23} actuators were placed on each of the four sides and driven at their resonance frequency (\(f_r = 500 \pm 20\) Hz). The excitation signal was subjected to amplitude modulation at relatively low frequencies (2–75 Hz) in order to introduce low-frequency disturbances. In later experiments,\textsuperscript{24} Wiltse and Glezer applied resonant forcing (\(f_r = 5092\) Hz) on one side only to excite the small scales in the dissipation range of the shear layer. Direct small-scale excitation resulted in enhanced energy transfer from the large to the small scales and in a substantial increase in the decay rate of turbulent kinetic energy.

In the present work, we attempt to use a moving wall section attached to a piezoelectric actuator to control the flow exiting a fully developed, turbulent channel flow with a rectangular cross section. In this case, the wall oscillates normal to the flow direction. This forcing arrangement was chosen for several reasons. The ceramic actuator is both durable and tunable. The amplitude and frequency can be tuned independently with a high degree of accuracy in order to achieve a variety of forcing conditions. The moving wall can eventually be implemented within an enclosed channel configuration. Finally, the moving wall can be used to alter particle motion in particle-laden flows, which will be investigated in future experiments.

The fully turbulent initial condition (as opposed to a more quiescent one) was chosen in order to conform with industrial flows. Furthermore, the initial flow conditions and the forcing boundary conditions (which can be documented to a high degree of accuracy) provide a case that can be computed numerically in order to test the accuracy of various numerical models. In this paper, we attempt to document how asymmetric disturbances propagate and evolve along and across the jet flow. In the following sections, we describe the experimental setup, the actuator performance, and the effect of various excitation conditions on the time-averaged quantities and frequency context within the jet.

II. FACILITY AND EXPERIMENTAL TECHNIQUES

A. Channel flow facility

The flow facility is a blower-driven channel that has been designed to generate a fully developed turbulent condition near its exit. The channel body, which can be seen in Fig. 1, consists of three main sections: the flow conditioning section, the development section, and the actuator section. The entire assembly is mounted vertically on a Unistrut frame with the air jet issuing into ambient, laboratory conditions. The air, which is driven by a frequency-controlled centrifugal blower, travels through a flexible hose and a laminar flow meter before it enters the top portion of the flow conditioning section. The air enters the channel through a set of four diametrically opposed ports at the upstream end. A series of grids and coarse and fine honeycombs are located in the flow conditioning section to eliminate swirl and to achieve uniformity across the channel span. The flow is subsequently tripped by two wires placed along the span of the channel at the entrance to the development section. Over a long time period, low frequency fluctuations in the bulk flow rate are less than 0.5% of the mean.
The length of the development section is 70w, where w represents the channel width of 15.75 mm. The cross-sectional area is constant with an aspect ratio of 11.45. As shown in Fig. 1, the development section consists of two aluminum side walls and two glass end walls. The glass walls are pressed against the aluminum ones with spacers. The lengths of the aluminum walls differ by 40 mm, which corresponds to the height of the moving wall section.

The moving wall consists of a rectangular plate attached to a piezoelectric actuator. A detail of the actuator section can be seen in Fig. 1. In the present configuration, the activated wall is located at the downstream end of the channel, oriented to generate wall-normal motions. The actuator is a PZT stack (Polytec-PI, model P-245.77) with a maximum displacement of 120 microns, a maximum operating voltage of 1000 volts and a resonant frequency of 2550 Hz. The displacement is directly proportional to the operating voltage. The actuator can sustain pulling forces up to 300 N, compressive forces up to 2000 N, and minimal shearing forces. The moving plate is made of aluminum and has a mass of 96 grams.

A linear amplifier (Polytec-PI, model P-270.10) is used to drive the piezoelectric translator. The maximum output voltage is 1000 volts with a negative polarity. The peak output current is 500 mA. The peak value of current required for sinusoidal operation of the translator can be calculated from the equation: $i_p = \pi \cdot f \cdot C \cdot V_i$, where $f$ is the frequency, $V_i$ is the peak voltage of the input signal to the actuator, and $C$ is the capacitance of the translator. For the P-245.77 translator used, $C = 0.5 \mu F$. Because the required input current is proportional to the product of frequency and peak input voltage, it scales directly with the peak velocity of the translator.

The piezoelectric translator can be operated in either open loop (uncontrolled) mode or closed loop (controlled) mode. In the open loop mode, the PZT ceramic exhibits time-dependent, long-term drift, hysteresis, and temperature dependence. These effects contribute to uncertainties and errors in the absolute position of the translator. The closed loop mode provides a means of minimizing these uncertainties by sensing and controlling the translator position. Strain gauge sensors attached to the stack are used to provide the control feedback. Although, the feedback circuit limits the maximum velocities achievable with the translator, its application is necessary to achieve repeatability and accuracy of the translator position. Therefore, for the experiments described, the translator was operated in the controlled mode.

### B. Actuator measurements

A laser vibrometer system (LV) was used to monitor both the velocity and displacement of the moving plate under various control conditions. The system consists of an optical head (Polytec, model OFV-352) and an electronic signal processor or velocity decoder (Polytec, model OFV-2600). The system operates as follows: a He–Ne laser beam is projected onto the oscillating surface (target) using a variable focus lens system that also serves as a collecting lens. A portion of the backscattered light is converted by a photodetector to an electric signal that is eventually output as a velocity reading based on the measured Doppler shift. The target displacement is determined by integrating the velocity signal. Over a measurement range of 0 to ±60 m/s, the system is specified to yield ±0.1% accuracy with a repeatability of ±0.02%.

For the experiments described, the optical head was oriented to reflect from the outer face of the moving plate. To increase signal-to-noise ratio, a piece of reflective tape was attached to the plate. Velocity and displacement measurements were made by holding the input frequency ($f$) fixed and increasing the peak-to-peak voltage ($V_{p-p}$) input to the amplifier from low values up to a maximum near 10 volts. This peak input corresponds to 1000 volts output to the actuator. For each set of inputs ($f$, $V_{p-p}$), the feedback loop was optimized for a step response by tuning the differential and integral terms of the controller. After the optimization procedure, the velocity and displacement of the moving plate were measured.

### C. Velocity and spectral measurements

Air flow at the exit plane of the channel was qualified with a single hot-wire probe. Also, detailed velocity measurements of the flow were obtained for a variety of control conditions. In all cases, a single sensor with diameter of five microns and a working length of 1.25 mm was employed in combination with a TSI IFA100 anemometer. The bridge output voltage was conditioned by passing it through an offset-and-gain configuration box and a low-pass filter. The conditioned signal was sent to a Macintosh Ilvxx computer, equipped with a multifunction I/O board (National Instruments, NB-MIO-16X). All data were collected on 12 bit A/D channels using Labview programs. The hot wire was calibrated against mean velocities obtained with a pitot probe attached to a manometer. During the calibration, the hot wire and pitot probe were placed adjacent to each other at the center of the channel exit plane. For each calibration, the channel was run at nine speeds, and a calibration curve was computed using King’s law. For time-averaged velocity measurements and flow qualification, 2048 samples per point were acquired at 50 Hz. These signals were filtered at 5.0 kHz. Spectral analysis was performed in the jet core and shear layers in both forced and unforced flows. For these studies, 35 files of 8192 points were acquired at a sampling rate of approximately 5.4 kHz. The signals were filtered at 2.6 kHz to prevent aliasing.

Uncertainties in single-sample velocity measurements resulted mainly from flow unsteadiness and the flow calibration, since the uncertainty due to the instrumentation accuracy was assumed to be negligibly small. Uncertainty due to flow unsteadiness was ±0.5%, and uncertainty in the flow calibration was ±0.5% for a single sample in the jet core and ±1.90% in the shear layer. Since velocity statistics were calculated from a finite number of samples, the statistics themselves have inherent uncertainties. Absolute uncertainty in mean velocity values was ±0.04($u'/U_{cl}$), where $u'$ was the streamwise rms velocity, and $U_{cl}$ was the centerline mean axial velocity. Absolute uncertainty in variance values was ±0.06($u'/U_{cl}$)². In the jet core, where $u'/U_{cl}$=5%, the uncertainty in the mean was ±0.20%. In the shear layers,
where $u'/U_{15}\approx 20\%$, the uncertainty in the mean was ±0.80%. The total uncertainty due to all sources was then ±0.77% for the mean and ±6% for the variance in the jet core region and ±2.12% for the mean and ±6% for the variance in the shear layers.

The probe holder was mounted on a horizontal traverse with an accuracy of ±0.01 mm. The probe was fixed at each vertical position with an accuracy of ±0.16 mm.

D. Flow visualization

Flow visualization was performed to assist in the interpretation of hot-wire results. Instantaneous images were obtained by illuminating smoke-seeded flow with a thin sheet from a Nd:YAG pulsed laser (Continuum Surelite I). The laser operating frequency and pulse duration were 10 Hz and 5–6 ns, respectively. A fog generator (Rosco 1500) was used to produce an aerosol of fine droplets (1–2 μm diameter) that were injected into the flow through the flow conditioning section of the channel. The light scattered perpendicular to the laser sheet was captured by a digital video camera (Sony, model DCR-TR7000, 30 frames per second).

III. RESULTS

A. Actuator performance

The overall performance of the actuator can be summarized by the two graphs shown in Fig. 2. In both graphs, the solid lines are linear fits to the individual data points plotted. Figure 2(a) shows the variation in the maximum displacement ($d_{\text{max}}$) of the moving plate in terms of the input frequency and peak-to-peak voltage. In the low frequency range ($35<f<110$ Hz), curves associated with individual frequencies coincide. The maximum displacement of 120 μm can be achieved when $9.5<V_{p-p}<10$ volts. As the frequency is increased ($200<f<400$ Hz), a dramatic decrease in the maximum displacement takes place. This occurs because of the maximum current limitation on the linear amplifier. Because of this limitation, the maximum input voltage has to be lowered, resulting in a narrower range of possible displacements.

In Fig. 2(b), the variation of the maximum velocity ($v_{\text{max}}$) of the moving plate is presented as a function of input frequency and amplitude. For low frequencies ($f\leq 110$ Hz), input frequency and amplitude increase directly with increasing velocity. At higher frequencies ($200<f<400$ Hz), the amplitude of the input voltage becomes more and more restricted, so that the maximum achievable velocity peaks and eventually decreases. One can observe that the maximum value of $v_{\text{max}}$ is limited to about 95 mm/s (see $f=200$ Hz and $V_{p-p}=7.5$ volts).

B. Flow conditions

An $(x,y,z)$ coordinate system is employed to describe the results (see Fig. 1). The $x$-axis originates at the channel exit and points downstream. The normal $y$-axis, originates at the channel center and points toward the moving plate. The $z$-axis runs along the span of the channel having its origin at the channel center. When the plate is not actuated, its inner face is aligned with $y/w=0.5$. In all of the experiments, the mean velocity of the unforced flow at the center of the channel exit was $U_{\text{unf}}(0,0)=4.14$ m/s, the turbulence level was 5%, and the Reynolds number (Re) based on this velocity and the channel width ($w$) was $Re=4240$. The maximum displacement of the moving plate ($d_{\text{max}}=120$ μm) corresponds to $y^+=1.84$ ($y^+=y/u_{\text{rms}}/v$; $u_{\text{rms}}$=shear velocity). Qualification measurements showed that the mean and rms velocities were uniform in the $z$ direction to within 1% over 60% of the channel span. The measurements described below were all taken at the mid-span of the channel.

In addition to unforced flow, a range of forcing conditions was investigated. The three cases investigated in most detail are characterized in Table I. Cases I and II are chosen to be within the low frequency range, where spectral mea-

<table>
<thead>
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<th>Case</th>
<th>$f$ (Hz)</th>
<th>$V_{p-p}$ (Volts)</th>
<th>$d_{\text{max}}$ (μm)</th>
<th>$v_{\text{max}}$ (mm/s)</th>
<th>$U_{\text{unf}}(0,0)$ (m/s)</th>
<th>$St$</th>
</tr>
</thead>
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<tr>
<td>I</td>
<td>65</td>
<td>9.5</td>
<td>115.2</td>
<td>47.0</td>
<td>4.14</td>
<td>0.25</td>
</tr>
<tr>
<td>II</td>
<td>110</td>
<td>9.5</td>
<td>114.8</td>
<td>79.5</td>
<td>4.14</td>
<td>0.42</td>
</tr>
<tr>
<td>III</td>
<td>385</td>
<td>4.0</td>
<td>31.9</td>
<td>80.1</td>
<td>4.14</td>
<td>1.46</td>
</tr>
</tbody>
</table>
measurements reveal strong energy content in the flow. Case III is chosen to be in the high frequency range where the energy within the flow is an order of magnitude smaller than in the other two cases. The maximum displacement of the plate is chosen to be the same for cases I and II, while the maximum velocity of the plate in case II is twice that of case I. The maximum velocity in cases II and III is the same. The last column of Table I corresponds to the Strouhal number (St) based on the frequency of the input signal, the channel width, and the mean, centerline velocity of the unforced flow \[St = f \cdot w / U_{\text{mid}}(0,0)\].

C. Flow visualization

The upper sequence of photos in Fig. 3 shows instantaneous smoke-marked images of the unforced jet taken in the \(x-y\) plane. The field of view, which extends to \(x/w = 6.5\), includes the silhouette of the channel exit with the moving wall section on the upper left side. In both images (a) and (b), the left and right shear layers appear to spread almost linearly with downstream distance. The linear spreading is more obvious when one superposes several instantaneous images of the unforced flow. In image (a), small-scale structures occupy the near field of the jet. In image (b), large eddies with length scale \(\sim w\) appear in the area close to the jet exit (\(1.0 < x/w < 3.0\)) while smaller eddies or structures exist further downstream. It is difficult to comment on whether or not these large-scale structures are associated with symmetric or antisymmetric modes of instabilities. However, since most of the eddies appear distorted and not well defined, one can conclude that the turbulent initial condition prevents any individual instability from dominating the overall flow structure.

The lower set of photos in Fig. 3 shows instantaneous images of the forced jet. The conditions are similar to those listed for case I. Forcing is applied at \(St = 0.27\), and the corresponding maximum displacement is 115.8 \(\mu\)m. This Strouhal number is near the low end of the range where the preferred mode is typically observed in round jets. In image (c), both large- and small-scale structures appear in the near field of the jet, and the overall flow resembles the unforced case in image (b). Image (d) clearly shows the existence of large, antisymmetric structures from \(x = 1.5w\) to \(4.5w\). In image (e), large symmetric structures occur. Therefore, both symmetric and antisymmetric modes of instabilities exist in the initial shear layers, and it appears that forcing increases their probability of occurrence. At the same time, structures associated with a wide range of frequencies persist owing to the turbulent initial condition.

As the forcing frequency is increased (\(St > 0.27\)), the size of the associated structures and the spacing between them decrease. No obvious changes in the jet structure were observable from the flow visualization (although the velocity measurements below show do exhibit changes). For lower frequencies (\(0.14 < St < 0.27\)), instantaneous images yield flow patterns similar to the ones observed for \(St = 0.27\).

D. Velocity measurements

The sequence of plots in Fig. 4 shows both forced and unforced mean and rms velocity profiles taken in the \(x-y\) plane at three streamwise locations (\(x/w = 1.4, 10\)). Both mean \(U(i,j)\) and rms \(u'(i,j)\) velocities [where \(i\) denotes the downstream location (\(x/w\)) and \(j\) denotes the cross-stream location (\(y/w\))] are normalized with respect to the local mean centerline velocity of the unforced case \(U_{\text{mid}}(i,0)\).

In Fig. 4(a), the mean profile of the unforced case at \(x/w = 1\) is symmetric with respect to the centerline, and its shape is typical of those found in fully developed turbulent channel flows. The side-wall boundary-layers measured at \((x/w, y/w) = (0, \pm 0.5)\) were found to be turbulent, and the velocity profile at \(x/w = 0\) is similar to the one shown. Symmetry persists further downstream, and the jet spreads with increasing streamwise distance [see Figs. 4(b) and 4(c), respectively]. Note that the \((y/w)\) scale in these plots changes with downstream location. The mean velocity profiles were found to be geometrically similar for \((x/w, y/w) = (0, \pm 0.5)\) when plotted against the parameter \(y/w = y/\delta_{0.5}\), where \(\delta_{0.5}\) is the jet width corresponding to one half of the mean centerline velocity. The self-similar velocity profiles agree well with those measured by Heskestad\(^6\) and Sfeir.\(^5\) In the present study, geometric similarity first occurred at an earlier axial location than those reported in previous studies (\(x/w \approx 30\)). The earlier occurrence of geometric similarity in the present flow can be explained by the higher turbulence intensity and thicker initial shear layers when compared with jets exiting contractions.

In Figs. 4(a), 4(b), and 4(c), the mean velocity profiles of all three forcing cases are symmetric with respect to the centerline. At \(x/w = 1\), the forced profiles lie on top of the unforced one except for \(St = 0.42\), where the velocity is larger in the outer region of both shear layers. At \(x/w = 4\), lower values of velocity with respect to the unforced ones are found close to the centerline for both \(St = 0.25\) and \(St = 0.42\), while no difference is observed between \(St = 1.46\) and the unforced case. Further downstream, at \(x/w = 10\), the profile corresponding with the lowest forcing frequency (\(St = 0.25\)) is broader, and the velocity decay is larger than in the other cases. At \(x/w = 10\), the profile of \(St = 1.46\) is not plotted because no differences in mean velocity between this case and the natural jet were found for \(x/w \geq 6\). In general, one can conclude that although the shape of the mean velocity profiles is not altered substantially, asymmetric excitation affects the downstream evolution of the centerline velocity.

The different forcing cases did alter the rms profiles as seen in Figs. 4(d), 4(e), and 4(f). At \(x/w = 1\), the unforced case yields a symmetric profile with a low turbulence level of 5% in the core surrounded by higher levels of 19% in the shear layers. The difference in core and shear layer turbulence levels decreases with downstream distance [see Figs. 4(e) and 4(f)]. At \(x/w = 10\), the difference in turbulence levels has decreased to 4%. Therefore, at further downstream locations the mixing initiated at the jet boundaries has permeated the entire flow field. The unforced rms profiles were symmetric at all measurement locations.

In the following paragraphs, the three forcing cases are
discussed. First, we consider the lowest forcing frequency, $St = 0.25$. At $x/w = 1$, the rms profile is asymmetric with respect to the centerline, and turbulence intensities are enhanced compared with the unforced ones. The enhancement is most obvious within the range $0 \leq y/w \leq 0.5$. A peak rms value of 0.21 is found at $y/w = 0.45$. At $x/w = 4$, increases in turbulence intensity have spread across the jet which has become more asymmetric. Specifically, the region of lower rms velocity has shifted off center, and the shear layer on the actuator side is broader as well as more energetic. The peak rms value of 0.21 is located at $y/w = 0.5$. At $x/w = 10$, the profiles appear symmetric. In fact, symmetric profiles were found for all $x/w > 2$. Hence, asymmetric disturbances induced at this frequency appear to permeate the entire flow by $x/w = 2$, and no evidence of a disturbance crossover is observed. At $x/w = 10$, the rms values are smaller than in the unforced case over the entire jet width. Therefore, turbulence reduction or suppression for $St = 0.25$ occurs sooner than for $St = 0.25$.

The third forcing case ($St = 1.46$) is similar to the second ($St = 0.42$) in that the average kinetic energy associated with the actuator was equivalent. Nevertheless, the higher frequency and smaller displacement corresponding with the third case was much less effective at altering the rms flow pattern. In all locations examined, no significant differences in rms velocity were found when comparing $St = 1.46$ with unforced flow.

In Fig. 5, the centerline evolution of the mean velocity decay, characterized by the parameter $\left[ \frac{U(i,0)}{U_{\text{inf}}(0,0)} \right]^{-2}$, is shown for both forced and unforced conditions. In the self-similar region of the unforced case ($x/w > 8$), this parameter varies linearly with the downstream location, as has been well documented in the existing literature. For $x/w \leq 3$, the four cases appear identical, suggesting that excita-
tion does not affect the velocity decay in this region. Further downstream ($x/w>3$), forcing at $St=0.25$ reveals larger values of decay. As the forcing frequency increases, however, the centerline velocity decay tends to approach that observed in the unforced case.

The phenomena of turbulence enhancement and suppression are considered further in Fig. 6, where the streamwise evolution of the normalized, centerline rms value is shown. The magnitude of the unforced rms value increases downstream of the jet exit and begins to level off near $x/w=10$ where it reaches a value of about 0.20. Heskestad\textsuperscript{6} and Sfeir\textsuperscript{5} reported values of 0.25 in the self-similar region of their jets. Forcing at $St=0.25$, causes strong enhancement of the rms values for $1<x/w<10$, while suppression occurs for $x/w>11$. The enhancement is maximized in the near field of the jet ($2<x/w<5$), while suppression appears to increase with downstream distance beyond $x/w=11$. Please note that despite persisting asymmetry in the rms profiles of $St=0.42$, the local centerline values are close to the minimum values measured, and the centerline evolution of rms values can be used to trace the evolution of both enhancement and suppression. For $St=0.42$, enhancement takes place within the range $1<x/w<5$, while suppression occurs for $x/w>6$. The amount of turbulence suppression seems to be constant for $8<x/w<13$ before it begins decreasing at $x/w=13$.

The initial streamwise location of the turbulence suppression is plotted as a function of frequency in Fig. 7. At $d_{max}=115\ \mu m$ and within the forcing range of $0.2<St<0.5$, suppression occurs at earlier downstream locations with increasing frequency. A linear curve fit to the log–log plot indicates that the streamwise location and the forcing frequency are related by a power law. For the case plotted, the linear fit corresponds to $x/w\sim St^{-1.085}$.

**FIG. 4.** Normalized unforced and forced mean and rms velocity profiles at three downstream locations ($x/w = 1, 4, \text{and } 10$).
E. Spectral measurements

Normalized power spectra of the axial velocity were measured for both unforced and forced cases in the range \( x/w = 1 - 10 \). Power spectra measured along the centerline and the actuator-side shear layer are plotted in Figs. 8 and 9 respectively.

The sequence of plots on the left-hand side of Fig. 8 corresponds to the natural jet. At \( x/w = 2 \) and 3, a hump between 60 and 120 Hz is observed. The corresponding Strouhal numbers vary from 0.23 to 0.42. This range of Strouhal number is typical of what one might expect for large symmetric structures developing across the jet span as was observed in Fig. 3. At \( x/w = 3 \), the hump contains peaks at \( St = 0.26 \) and 0.37. Wiltsie and Glezer\(^{23}\) mentioned the existence of a similar hump in the near field of their square jet. The power spectrum of their unforced jet at \( x/D_e = 5 \) revealed a hump centered at \( f = 35 \) Hz, corresponding to a Strouhal number \( St_{D_e} = 0.38 \). At \( x/w = 4 \), the hump in our rectangular jet has practically disappeared. Additional plots show that, further downstream, energy shifts toward the highest frequencies plotted, implying that energy is transferred from lower to higher frequencies as larger structures break down. Smaller structures downstream of larger ones are seen clearly in Fig. 3.

The plots on the right-hand side of Fig. 8 correspond to the forced case of \( St = 0.40 \). The conditions are very similar to those listed for case II. Strong peaks at the forcing frequency occur for \( 1 < x/w < 5 \). The peak at the forcing frequency is strongest at \( x/w = 2 \) and decreases monotonically with streamwise distance. When \( x/w < 3 \), peaks are also present at twice the forcing frequency. These harmonics most likely result from out of phase fundamental (or antisymmetric) structures developing on opposite sides of the core and extending across the centerline. Also, a peak at one half of the forcing frequency appears for \( x/w = 2 - 3 \). This peak, which is broader than the fundamental peak and strongest at \( x/w = 3 \), indicates possibly the presence of paired structures. Outside of the locations of the strong peaks, the normalized energy in the forced spectra is suppressed compared with the unforced flow. In addition, the broad-hump characteristic of the unforced flow does not appear. Figure 8 thus demonstrates that forcing at this frequency has altered the structure in the jet core significantly.

The spectral evolution along the actuator-side shear layer is examined in Fig. 9 for both unforced and forced conditions. All measurements were obtained at the spanwise location where the rms value was a maximum. In the near field of the natural jet (\( 1 < x/w < 4 \)), highly energetic fluid exists at low frequencies (20–150 Hz). For \( St = 0.40 \), strong peaks at the forcing frequency are observed within the same range. At \( x/w = 1 \), additional harmonics are present. These are thought to be caused by harmonics within the moving wall. (Such harmonics were observed also in laser vibrometer measurements of the wall displacement.) Note that these harmonic disturbances die out quickly. At \( x/w = 2 \), only a weak peak at twice the forcing frequency can be observed.

At \( x/w = 1 \), a distinct hump that covers a frequency...
range from 80 to 140 Hz is observed in the forced flow. The presence of this hump suggests that the forcing enhances structures not only at the forcing frequency, but also over a fairly broad frequency range surrounding it. At $x/w = 2$ and 3, the hump narrows and shifts toward lower frequencies, while at $x/w = 4$, the hump has disappeared. Further downstream ($x/w > 5$), significant differences between unforced and forced spectra were not detected.

Separate measurements (not shown) revealed spectra along the opposing shear layer that were identical to the spectra on the actuator side. This reinforces our observation that asymmetric forcing with $St > 0.40$ generates disturbances felt equally by points located on either side of the centerline for $x/w > 1$.

Next we consider spectra for $St = 0.25$ (case I). Measurements along the centerline (not shown) revealed that the spectral evolution is similar to that described for $St = 0.40$.

Strong peaks at the forcing frequency are observed within the range $1 \leq x/w \leq 6$, while peaks at twice the forcing frequency are detected for $x/w \leq 4$. The peaks persist slightly longer than when $St = 0.40$ indicating that the larger structures formed at the lower frequency remain coherent over a longer distance. Again, the persistence of the harmonic peak along the centerline is consistent with the presence of staggered antisymmetric vortices as observed in Fig. 3(d). It is worth mentioning that no peak appears at one-half of the forcing frequency on the centerline for this case.

Figure 10 reveals the asymmetry in the spectra along both shear layers for $St = 0.25$. As before, these spectra were measured at spanwise locations where the maximum rms values were detected. On the actuator side, strong peaks at the forcing frequency are observed from $x/w = 1$ to 4, while peaks at additional harmonics occurred also for $x/w = 1$ and 2. At $x/w = 2$, a distinct hump covers the range of 50–100

FIG. 8. Normalized power spectral density functions along the centerline for unforced flow (left) and flow forced at $St = 0.40$ (right).
Hz. The hump subsequently narrows and decreases in strength, disappearing by \(x/w = 4\). On the opposing wall side, strong peaks at the forcing frequency are detected over a greater streamwise distance (1 \(\leq x/w \leq 6\)), and peaks at twice the forcing frequency are found at \(x/w = 2\) and 3. The presence of the harmonic peaks can be explained by antisymmetric structures generated on the actuator side that are felt all the way across the jet. Relatively broad peaks at half the forcing frequency, indicating the presence of paired structures, are observed at \(x/w = 5\) and 6. Further downstream (\(x/w \geq 8\)), the wall-side spectra appear similar to these on the actuator side of the jet.

The existence of strong peaks on the wall side at streamwise locations where the corresponding spectra in the actuator-side shear layer are featureless is consistent with the rms velocity behavior shown in Fig. 4. The spectra show that the large structures forming at the forcing frequency persist over longer distances in the wall-side shear layer. Therefore, although higher rms values are initially closer to the actuator due to the immediate formation of structures there, further downstream, the peak rms switches to the unforced side [see again Fig. 3(d)].

Forcing at \(St = 1.46\) (case III) results in spectra with narrow peaks at the forcing frequency. Outside of these peaks, the shapes of the forced spectra are similar to the unforced ones. The values of the peaks measured on the centerline and in the shear layers are smaller than those for \(St = 0.40\), leading to the conclusion that high frequency disturbances are dissipated more quickly than those at lower frequencies. This behavior was demonstrated also by Wiltse and Glezer. In their jet, the high frequency component of the carrier waveform was barely noticeable even at \(x/D_e = 1\). Conversely, low frequency disturbances (0.10 < \(St_{p_e} < 0.80\)) introduced
via their amplitude modulation scheme persisted for longer distances downstream (e.g., at $f = 16$ Hz, corresponding to $St_{D_e} = 0.174$, strong low frequency peaks could be found up to $x/D_e = 4$).

Based on additional spectra measured at $x/w = 1$ and $y_{0.5} = \pm 1$ within the range $0.13 < St < 0.46$, the following remarks can be made. Forcing within the range $0.13 < St < 0.38$ yields spectra with stronger peaks on the actuator side than on the opposing side. As the forcing frequency increases (while the amplitude is held constant), the difference in magnitude between the peaks decreases until it reaches zero near $St = 0.38$. For $St > 0.39$, asymmetric disturbances are felt equally by points located in either shear layer.

For $St = 0.40$, then, the strong and wide hump observed at $x/w = 1$ (see Fig. 9) occurs in both shear layers. As the forcing frequency decreases ($St = 0.39$ to $0.29$), the humps on both sides become narrower and weaker. The hump on the opposing side weakens faster. Eventually, at $St = 0.25$, no hump surrounding the forcing frequency remains in either shear layer at $x/w = 1$ (refer to Fig. 10). The spectral results thus demonstrate that forcing at an intermediate frequency ($0.39 < St < 0.46$) almost immediately excites structures over a band of frequencies surrounding it. Forcing at a lower frequency ($St = 0.25$), also excites a localized frequency band, but this does not occur until $x/w = 2$. Forcing at a higher frequency ($St > 0.60$), however, enhances structures only at the forcing frequency or its harmonics.

**IV. SUMMARY AND CONCLUDING REMARKS**

The experiments discussed have demonstrated an active control method for manipulating turbulent flow exiting a channel. The control scheme consists of a rectangular plate attached to a piezoelectric actuator that is oriented to gener-

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**FIG. 10.** Normalized power spectral density functions along the actuator-side shear layer (left) and the wall-side shear layer (right) for $St = 0.25$. 
ate wall normal motions. The actuator allows the wall velocity and displacement to be controlled and tuned independently. In the experiments described, the maximum achievable velocity was 2.3% of the mean centerline velocity at the channel exit. The maximum displacement of the moving plate corresponded to 1.84 wall units.

Three forcing cases as well as an unforced case were examined in detail. Both the actuator displacement and velocity were characterized to high accuracy providing precise initial conditions for numerical codes. Hot-wire measurements show that forcing can affect both the mean and rms velocities. Compared with the unforced jet, forcing at low frequencies ($St \leq 0.30$) causes faster decay of the mean centerline velocity as well as higher spreading rates in the far field. Although mean velocity profiles are symmetric with respect to the centerline, rms profiles are asymmetric. Fluctuation levels are increased with respect to the unforced case in the near field of the jet, while further downstream a comparative reduction in turbulence takes place. The most striking feature of the low frequency forcing case is the propagation of the maximum rms value from the actuator-side shear layer to the opposite one with increasing streamwise distance. This behavior is attributed to the existence of low frequency staggered structures that maintain their coherence further downstream on the unforced side of the jet.

Forcing at intermediate frequencies ($0.39 < St < 0.60$) yields mean velocity profiles similar to the unforced ones. Thus, this forcing has a minimal effect on both the mean centerline velocity decay and the jet spreading rate. Unlike the lower frequency case, the time-averaged rms velocity profiles and spectral behavior are symmetric with respect to the centerline already by $x/w = 1$. These higher frequency perturbations, therefore, propagate quickly across the jet width so that the resulting flow modification is equivalent on both sides. Spectra reveal evidence of staggered vortical structures occurring in the jet nearfield. Again, rms fluctuation levels are increased with respect to the unforced case in the near field, while a turbulence reduction occurs further downstream. This crossover from turbulence enhancement to reduction, also found in the low frequency range, depends on both the forcing frequency and the maximum displacement of the moving plate. Earlier studies by Zaman and Hussain demonstrated immediate turbulence suppression over a range of forcing frequencies in forced round and rectangular jets. Their initial conditions, however, were significantly different from those in the present study. In their case, the flow issued from a contraction with thin laminar boundary layers, and the initial core turbulence level was only 0.25%. In fact, when their boundary layers were tripped, no suppression was observed.

Finally, forcing at an even higher frequency (e.g., $St = 1.46$) reveals no change in time-averaged flow statistics compared with the unforced flow. Both the mean and rms velocity profiles are similar to the natural ones. Although the average kinetic energy of the actuator was equivalent to the case studied at an intermediate frequency, the flow was not receptive to the excitations, and the disturbances were quickly attenuated. The high frequency case comes closest to the flow of Wiltse and Glezer which was forced at substantially higher frequency and amplitude. (The actuator tip velocity was approximately 66% of the mean exit velocity). The large forcing amplitude resulted in a crossover from turbulence enhancement to reduction close to the jet exit ($x/D_p \sim 1$).

**ACKNOWLEDGMENTS**

This work was funded by grants from the ACS Petroleum Research Fund (32524-AC9) and the National Science Foundation (CTS 945-7014).

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