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The Preferred and Shear Layer Modes in a Jet under Passive Controls

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Abstract

The structure of a round, free, turbulent jet was modified by placing a passive ring near the nozzle exit. A single hot wire was used to measure the jet flow field. The ring was designed such that it was placed in the middle of the shear layer near the jet exit. The results show a considerable reduction in the jet spread rate and turbulence intensity when the passive ring is employed. The instability spectra studies show the suppression of the initial shear layer instability (shear layer mode) while the jet preferred instability (preferred mode) remains active as the shear layer is modified. This shows the separation of these modes.

Introduction

The control of turbulence in jet flows has been the subject of a large number of studies because of its potential benefits in industry. Different methods were employed to modify the turbulence characteristics of jet flows. The common objective of effective control strategies was to target the large scale coherent structures. The near field development of a round jet is strongly characterized by a regular vortex structure (organized transitional flow) that results from the initial instability. This structure is amplified and subsequently form large eddies. These large eddies are unstable and break down to form smaller structures. Therefore, the control of the fluid in the near- to intermediate-field region (NIF) that employs different methods to change the initial mean profile (passive methods) or excitation at a particular frequency (active methods) have received significant attention in literature. Crow and Champagne [1] studied the effect of changing the initial conditions of a jet through the controlled excitation of the boundary layer upstream of the nozzle in the plenum chamber and introduced the jet preferred mode as a global instability of the entire jet column in addition to the well-known shear layer mode. Hussain and Zaman [5] employed the controlled excitation to improve detection of coherent structures in the near field of a round jet. Using the controlled excitation, they were able to diminish the turbulence level in the near field of different jets. They also found that while the preferred-mode coherent structures were independent of the nature of the initial shear layer (laminar or turbulent), the size and orientation of the structures were Reynolds number dependent. Petersen and Samet [7] investigated the instability of the preferred mode and demonstrated that there is no distinction between the shear layer mode and the preferred mode. This finding does not agree with the earlier work of Hussain and Zaman [5] who concluded that the jet preferred mode is decoupled to the shear layer mode.

Using passive methods, Tong and Warhaft [8] and Parker et al. [6] studied the near- and intermediate-fields of circular jets using fine circular wires. They found a significant reduction in RMS axial velocity fluctuations and a shift in the virtual origin.

The main objective of the present paper is to gain deeper insight into the effects of using a passive control device on the near-intermediate-fields of a round, turbulent jet through the introduction of a single ring placed in the jet shear layer region. The current paper investigates the near-lip shear layer mode and the preferred mode for both modified and unmodified jets to help resolve the contradiction noted in the literature on the relationship between these two modes (Hussain and Zaman [5] and Petersen and Samet [7]).

Experimental Conditions

Air exits a settling chamber via a round duct to the inlet of smoothly contracting axisymmetric nozzle with exit diameter of D = 73.6 mm. The mean and RMS velocity profile at the jet exit were carefully measured (x/D = 0.03) with a stationary single hot wire. A wire ring, with square cross-section, of sides h = 1.5 mm, and outer diameter D_{wire} = 71.6 mm was placed in the middle of the jet shear layer, at a stand-off distance downstream of the jet nozzle exit plane x/D = 0.03. The ring was designed to enable computational studies to be considered using simple cylindrical-polar co-ordinates. Figure 1 provides views of the exit nozzle and the passive ring placed in the shear layer. As can be seen, the ring was carefully designed and placed in the shear layer near the exit such that it was not under vibration.

Data were acquired using a static hot-wire, at Re = 30,000 (Re = U_jD/υ), which is beyond the mixing transition, see Dimotakis [2] and Fellouah and Pollard [3].

The exit mean velocity profile is uniform over the range of $0 \leq r/D \leq 0.45$ and decreases to zero between $0.45 < r/D \leq 0.5$ (inside the shear layer). It should be noted that the ring covers the distance of $0.466 \leq r/D \leq 0.486$ (figure 2). The boundary layer characteristics for the unmodified jet at the exit are listed in table 1. The shape factor is slightly higher than the Blasius flat plate value (H = 2.59) and indicate that the boundary layer is close to laminar at the current Reynolds numbers.

Figure 1. Views of the exit nozzle (upper figure) and the passive ring placed in the shear layer (lower figure).

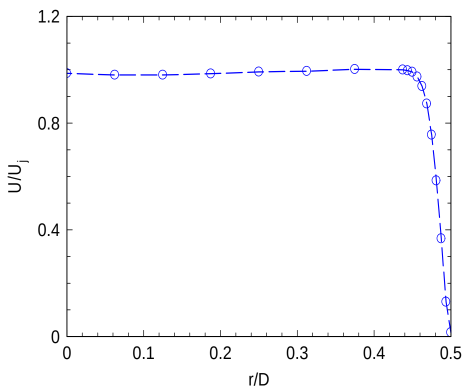


Figure 2. Streamwise mean velocity at x/D = 0.03 for Re = 30000.

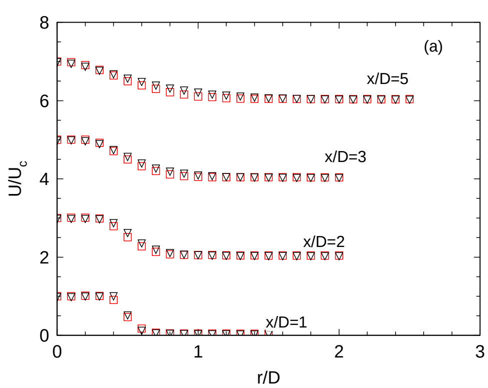
U_j (m/s)	δ^* (mm)	θ (mm)	H	Potential core turbulence (%)
6.39	1.31	0.44	2.97	0.72

Table 1. Nozzle exit boundary layer statics (Re = 30000 and x/D = 0.03)

Results

Mean Velocity

The ratio of the normalized mean velocities (relative to the local centreline value) at different axial locations, for with and without ring cases is presented in figure 3, all at Re = 30000. It can be observed that the jet radius is hardly affected by the introduction of the rings, although there appears to be some effect farther downstream in the intermediate region.



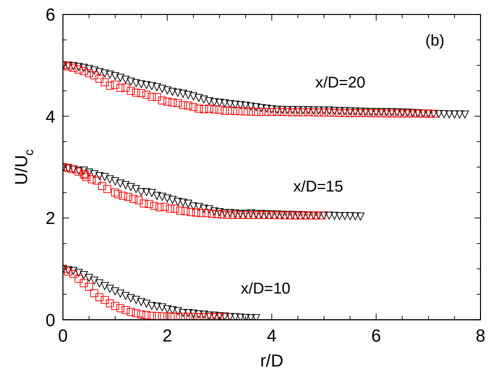


Figure 3. Streamwise mean velocity at different axial locations for Re = 30000. Open triangle ▽: no ring; open square □: with ring. (a) The near field region from x/D = 1-5 (b) The intermediate region x/D = 10-20. Note that each curve is shifted by 2 with respect to lower one.

RMS Velocity

Figure 4 provides a plot of the radial turbulence intensities normalized by the jet exit mean velocity for different axial locations at Re = 30000. The reduction in the magnitude of the turbulence intensities in the near field agrees with the assumption that the rings suppress large-scale turbulence structure. Also, it is not until about x/D = 15 that the influence of the rings apparently disappears.

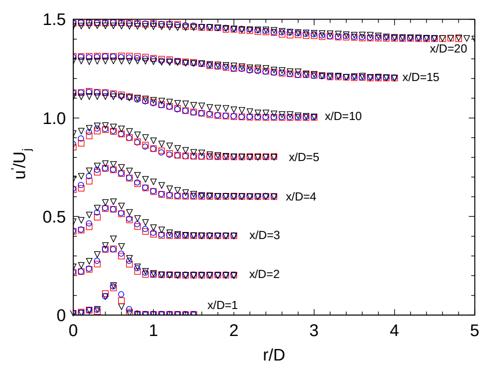


Figure 4. Axial evolution of the turbulence intensities for Re = 30000. Open triangle ▽: no ring; open square □: with ring. Note that each curve is shifted by 0.2 with respect to lower one.

Power Spectra Density

It is known that the near field of a jet consists of two flow instability modes. The first is the shear layer mode, which is associated with a high frequency oscillation due to the roll-up of a shear layer separated from the nozzle lip. In other words, for an initially laminar free shear layer, the initial (Kelvin-Helmholtz) instability produces roll-up of the shear layer through nonlinear saturation. This structure scales on the characteristics thickness of shear layer (the exit momentum thickness). The large structure of this kind in the mixing layer of a jet was extensively studied using both hot wire measurements and flow visualization by Yule [9]. The other kind of instability is called the jet preferred mode. The concept of the preferred mode of jet instability was introduced by Crow & Champagne [1] to describe the response of their axisymmetric jet to externally imposed axisymmetric excitations. The term was used to denote the mode that attained the maximum growth under nonlinear saturation. Their measurements were taken at a fixed location on the jet centreline four diameters downstream from the jet exit plane. The frequency of the preferred mode was observed to scale with jet velocity U_{jet}

and diameter D such that $f = 0.3U_{jet}/D$, and they conjectured that the mode was a global instability of the entire jet column. Hussain and Zaman [5] commented that the preferred mode instability characteristics are independent of whether the initial shear layer is laminar or fully turbulent. They were able to select one type of instability at a time by means of controlled excitation and suggested the separation of the preferred mode and shear layer. However, Petersen and Samet [7] suggested an alternative relationship between this mode and the shear layer mode. They argued that there is no distinction between these modes and claimed that the preferred mode is actually the shear layer mode that is most amplified by x/D = 4.

Here, the power spectrum of the fluctuating velocity is used to isolate vortex-shedding events. Measurements were performed behind the rings to study the shear layer mode and along the jet axis to investigate the preferred mode.

The investigation of the different instability modes begins with the shear layer mode. All samples were taken at a fixed location in the shear layer (r/D = 0.476 which is behind the ring). Starting from the shear layer of the unmodified jet, the normalized power spectral density between 0.4 < x/D < 5 is presented in figure 5. For the unmodified jet and at x/D = 0.4, the largest peak frequency is found at approximately f_s = 240 Hz. This is equivalent to a Strouhal number, St_θ, of 0.0165 ($St_\theta = f_s\theta_{exit}/U_{jet}$ and θ_{exit} is the exit momentum thickness without ring), which is within the expected range for the shear layer instability from 0.01 to 0.018 Gutmark and Ho [4]. In fact, this implies a large coherent structure within the jet near field, which results from the roll-up of the initial shear layer (the shear layer mode). At streamwise locations farther downstream, the largest peaks shift at near sub-multiples of the roll-up frequency (118 Hz and 55 Hz), which implies interactions of the shear layer instability structures or stable vortex pairing activity in the mixing layer. It should be pointed out that close to the nozzle, there are occasional other peaks that are probably indicative of azimuthal instabilities, which are not associated with the roll up of the shear layer.

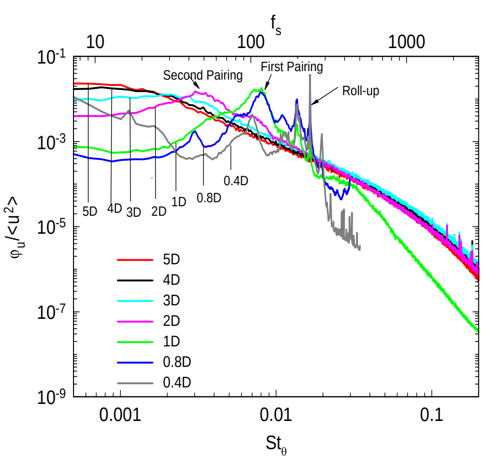


Figure 5. Normalized streamwise power spectra at different axial locations and r/D = 0.476 for unmodified jet $St_\theta = f_s\theta_{exit}/U_{jet}$ (Re = 30000).

In order to study the effect of rings on the mixing layer spectra at similar locations, the velocity spectra at r/D = 0.476 are plotted in the presence of the ring (figure 6). In figure 6, a small peak at x/D = 0.4 can be observed. As this peak appears at a frequency ~ 240 Hz, which is equal to the roll-up frequency, which implies that the ring does not produce a new spectral mode and the natural roll-up mode still occurs even at a considerably lower disturbance level (low power spectra level). This suggests there is a weak vortical structure when compared to an unmodified jet. Slightly farther downstream and beyond x/D = 1, all peaks at the fundamental frequency disappear and velocity spectra display apparently fully turbulent flow as characterized by Yule [9]. In other words, the power spectra no longer display vortex pairing events, and it is concluded that transition to fully turbulent flow occurs earlier when a ring is used. This is due to the interaction of the ring wake with the shear layer, which causes earlier breakdown of organized structures of the shear layer mode and occurrence of fully turbulent flow.

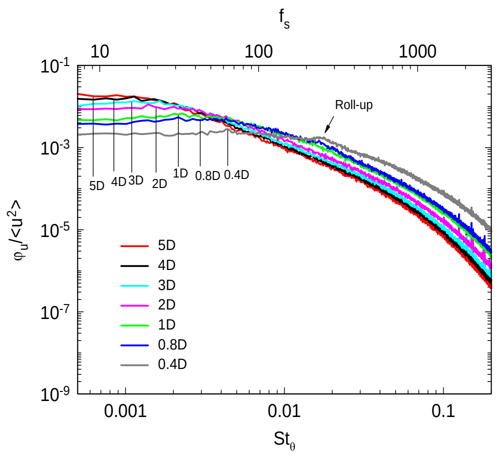


Figure 6. Normalized streamwise power spectra at different axial locations and r/D = 0.476 for modified jet $St_\theta = f_s\theta_{exit}/U_{jet}$ (Re = 30000).

In order to study the preferred mode of the jet, the spectra of the streamwise velocity along the axis of the jet for the two physical conditions considered at Re = 30000 are provided in figures 7-8. In these plots, the frequency is normalized using the exit velocity and the jet diameter ($St_D = fD/U_{jet}$). Starting from the unmodified jet in figure 7, the spectra show a peak at St_D = 0.56 from the near exit until the end of potential core (from x/D = 0.4 until x/D = 4). This Strouhal number is within the usual range for the jet preferred mode (e.g., Gutmark and Ho [4]). It is noted from figure 5, the vortex second pair (shear layer mode) is close to this preferred mode frequency, so it may be assumed they are connected to each other. However, as can be seen in figure 8, the jet preferred mode at approximately the same St_D is observed. As it was shown before, when the jet is modified using the ring, the shear layer mode is suppressed and all stable vortex pairings have disappeared; however, the jet preferred mode remains active for the modified jets. This clearly indicates that these two modes cannot be related through vortex pairing of the shear layer mode.

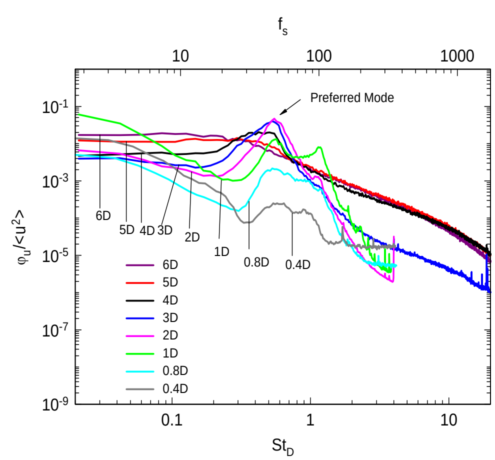


Figure 7. Normalized streamwise power spectra at different axial locations and r/D = 0 for unmodified jet (Re = 30000).

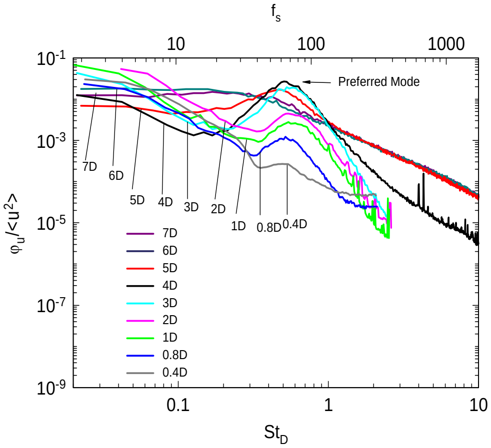


Figure 8. Normalized streamwise power spectra at different axial locations and r/D = 0 for modified jet (Re = 30000).

Conclusions

The current paper considered the effect of a thin square ring placed inside the shear layer on the round free jet behavior. The reduction in the jet spread rate and a small increase in the potential core region were found in the case when the ring was used. The turbulence intensity is considerably suppressed in the near field. The radial velocity profiles revealed that the jet width decreased when the jet was modified.

The spectra results showed that the weak vortex roll-up was altered when the ring was employed. However, the stable vortex pairing of the shear layer mode completely disappeared for the with-ring case and an earlier transition to fully developed turbulence was found. Once the shear layer was suppressed, the jet preferred mode remained active. This suggested that the jet preferred mode could be captured independently of the shear layer mode. This finding is close to what Hussein and Zaman [5] suggested, but contradicts Peterson and Samet [7] who claimed that the shear layer mode and the jet preferred mode cannot be separated and in fact the jet preferred mode is the evolution of the shear layer mode.

Acknowledgments

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