Flow Structures of a Basic Annular Jet

N. W. M. Ko* and K. M. Lam†
University of Hong Kong, Hong Kong

This paper describes the modal expansion and conditional sampling results of static pressure fluctuations in the inner and outer mixing regions of a basic annular jet. An understanding of the mechanism of the wake shedding process from the internal recirculating region behind the blunt interface is attempted by conditionally sampled pressure signals. The evolution and characteristics of the shedding wake, wake-induced vortices, and jet vortices in both shear layers are measured and presented. The evolution of the wake-induced vortices in the outer shear layer as a result of excitation by the disturbances associated with the shedding wakes is further supported.

Introduction

THE flow characteristics of the initial region of an annular jet discharging into stationary air have been investigated previously.[1-4] Chigier and Beer[1] and Williams et al.[2] studied them as a limiting case of a coaxial jet. Because the configuration of the annular jet adopted by the above workers was without any afterbody or bullet at the nozzle exit, an internal recirculating region was formed downstream of the interface.[1,3] This internal region was the result of the absence of any supply air in the center and the entrainment of air from the main stream of the annular jet. In this recirculating region subatmospheric pressure and standing vortices were found. The extent of the standing vortices, the recirculating mass flow rate, and the subatmospheric pressure depended on both the blockage ratio $(D_i/D_o)^2$ and the divergent angle α of the forebody.[3]

The recent studies of annular jets concerned not only the basic annular jet, in which there is no bullet or afterbody in the center of the jet, but also the conical jet if such a conical bullet were present.[5-7] Based on velocity and pressure spectral measurements, one type of coherent structure was found in the outer mixing region of either type of annular jet as the result of the shearing of the fast-moving potential core fluid with the ambient air. The mean velocity, turbulence intensity, and the characteristics of the coherent structures agreed with those of a single jet. Hence these types of coherent structures generated within the outer mixing region of the annular jet, whether or not there was an internal recirculating region behind the interface, was termed the outer jet vortex.

In the case of the basic annular jet, another type of coherent structure was found in the outer mixing region, in addition to those associated with the outer jet vortices.[5] This additional structure, termed the wake-induced vortex, seemed to be the consequence of the presence of the internal recirculating region and the shedding of the standing vortices or the wake vortices downstream of the blunt interface.[5,6] Both the outer jet vortices and wake-induced vortices have, besides the axisymmetrical mode constituents, azimuthal constituents. The constituent of the first mode could be as dominant as that of the axisymmetrical.[7] The existence and dominance of the wake-induced vortices depended on the diameter ratio D_i/D_o. For large diameter ratios, the wake-induced vortices seemed to be more dominant.

The investigation of the influence of the shedding wakes and their associated disturbances on the initial outer shear layers and the subsequent evolution of the induced structures may help to further clarify the phenomena of shear layer excitation and large-scale structure dynamics which are fundamental in the study of turbulent free shear flows. Moreover, the inner region resembles that of a near wake behind an axisymmetric blunt body. Similar studies are rare and the ones reported are limited primarily to the case of a disk in cross flow.

The present investigation was an attempt to understand the mechanism of the wake shedding process from the internal recirculating region in the near wake of the blunt interface and the mode of evolution of the wake-induced vortices in the outer mixing region. This paper documents the results and interpretations based primarily on a mode expansion technique and a time domain analysis on the static pressure fluctuations. Measurements of the velocity fluctuations are being carried out and will be reported separately.

Experimental Apparatus

The test rig for the air jet has been described in detail in Ref. 5. The outer diameter D_o of the jet was 6.2 cm, and the diameter of the interface D_i was 2.8 cm, giving a diameter ratio D_i/D_o of 0.45 (Fig. 1). The divergent angle α of the forebody was 0 deg. The jet exit velocity $\bar{U}_0$ was 50 ms^{-1} and the two boundary layers were laminar. The Reynolds number, based on the outer diameter, was 2×10^5.

The pressure fluctuations of the air jet were obtained by using a Brüel and Kjaer ⅛ in. condenser microphone with a standard nose cone. The microphones were placed with the nose cones pointing upstream and their axes parallel to the

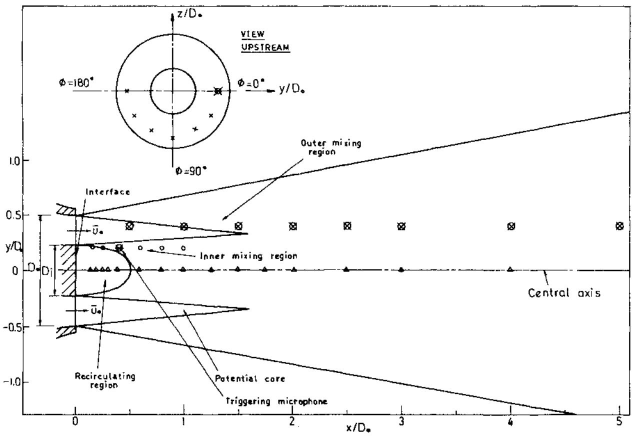

Fig. 1 Schematic diagram of basic annular jet. 0, fixed microphones for cross-spectral and modal analyses; *, triggering microphone; Δ, recovery microphone at jet central axis; ×, recovery microphone at $r/D_o = 0.4$.

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*Reader, Department of Mechanical Engineering.

†Graduate Student, Department of Mechanical Engineering.

jet central axis so as to obtain the static pressure fluctuations.[10] A Hewlett-Packard Model 5423A structural dynamic analyzer was used for the auto- and cross-spectral, coherence, and conditional sampling measurements. The complex two-point cross-spectral density function R_ω is defined as

$$R_\omega = C_\omega + j\, Q_\omega = |R_\omega| \exp j\, \psi_\omega$$

where C_ω and Q_ω are the coincident and quadrature spectra and ψ_ω the phase angle between the signals from the two microphones.

Experiments were carried out within the initial region of the basic annular jet, $x/D_o < 5$. The radial positions chosen were at $r/D_o = 0.4$ and 0.2, the former being within the outer mixing region and the latter within the inner mixing region (Fig. 1). Circumferential coherence measurements on these radii were made at fixed streamwise stations such that a modal analysis could be carried out. The decomposition of the pressure fluctuations into different azimuthal constituents was based on the technique of Fuchs et al.[8] and Michalke and Fuchs.[9] Based on the assumptions of no preferred helical propagation for the disturbances, symmetry in $\Delta\phi$, and periodicity of 2π, the normalized Fourier analysis gives

$$\frac{C_\omega(\Delta\phi)}{\overline{p_\omega^2}} = \sum_{m=0}^{\infty} \frac{C_{\omega,m}}{\overline{p_\omega^2}} \cos m\Delta\phi$$

The nondimensionalized energy within different modes is given by

$$\overline{p_{\omega,m}^2} = C_{\omega,m} \cdot \overline{p_\omega^2}$$

A time domain analysis of the pressure fluctuations across the basic annular jet was also performed. The analysis was based on the conditional sampling technique of Lau and Fisher[10] and Bruun.[11] Within this set, two series were obtained (Fig.1). The first and more elaborate series had the triggering microphone A located at $x/D_o = 0.4$, $r/D_o = 0.2$, $\phi = 0$ deg. This was within the inner mixing region and the pressure signal consisted of substantial contributions from the wake vortices.[5] Positive pressure was used in the triggering. The pressure signals were first recovered along the jet axis and then at different azimuthal angles on the circumference of $r/D_o = 0.4$. The size of the triggering probe relative to the inner shear layer width might introduce uncertainties in the interpretation of the results. In order to understand if there was any effect of the upstream probe on the downstream one, another series of measurements was performed. The second series had the triggering microphone located within the outer mixing region ($x/D_o = 1.5$, $r/D_o = 0.4$, $\phi = 0$ deg). Positive pressure was also used in the triggering. The signals along the jet axis were recovered. Apart from the slight differences in the averaged pressure intensities, the recovered pressure signals along the jet central axis are very similar in both series, indicating that the size and position of the triggering microphone A did not significantly affect the evolution of the large-scale structure. Thus, the results of the second series are not presented herein.

Results and Discussion

The time domain analysis of the pressure fluctuations was based on conditional sampling with reference to the shedding of the wake vortices. As has been shown by Ko and Chan,[5] the shedding of the wake vortices within the inner region occurs at the boundary of the internal recirculating region. Thus, the triggering microphone was located at $x/D_o = 0.4$, $r/D_o = 0.2$, $\phi = 0$ deg. At this position the time trace of the pressure signal contains distinct, fairly regular positive peaks. A rough estimate of the frequency gives a value of about 420 Hz ($St_i = fD_i/\bar{U}_0 = 0.238$), which is near the wake vortex frequency. A triggering level of $+2\,\sigma_p$ was chosen, where σ_p is the rms value of the triggering pressure signal. Whenever the triggering signal rose above this threshold level with positive slope, a time record of both the signals from the triggering and recovery microphones with appropriate pre- and post-trigger delay periods was sampled. The final recovered traces were obtained by ensemble averaging of 1000-1500 samples. The ensemble size was large enough to ensure convergence.

The recovered pressure signals at the jet central axis ($r/D_o = 0$) and within the recirculating region ($x/D_o \leq 0.4$) are shown in Fig. 2, in which flow events A and B and 1 and 2 are indicated. For events A and B, pressures below the local mean static pressure are recovered. Since the locations are within the recirculating region, one would not expect these pressure troughs to be associated with the passage of a convecting, well-organized vortex structure.[10] Therefore, they are likely to be due to a momentary partial vacuum in that region immediately after the regular shedding of fluid masses at and near the interface. Likewise, flow events 1 and 2 with positive pressures are due to the aggregation of fluid mass in the recirculating region prior to the periodic shedding. Additional evidence can be found from the recovered pressure signals shown in Fig. 2.

The propagation of flow event A downstream is accompanied by increasing negative pressures. This represents the partial vacuum in the recirculating region originating from the shedding of the wake at $x/D_o = 0.4$. For flow event 1 the pressure increases from slightly subatmospheric near the nozzle exit to above atmospheric at $x/D_o = 0.4$. Hence this downstream flow event represents an aggregation of fluid up to $x/D_o = 0.4$, where subsequent shedding occurs. Besides flow events A and 1, there is another pair of events B and 2 which seem to be combined into event 1 at locations upstream of $x/D_o = 0.4$. The origin of this additional pair is not yet known, but it seems to be caused by the behavior of the recirculating region on the diametrically opposite plane ($\phi = 180$ deg).

At $x/D_o = 0.25$, the signals at other radial and annular positions have also been recovered (Fig. 3). On the $\phi = 60$ deg plane, the positive peak associated with flow event 1 seems to convect toward the jet central axis, suggesting inward

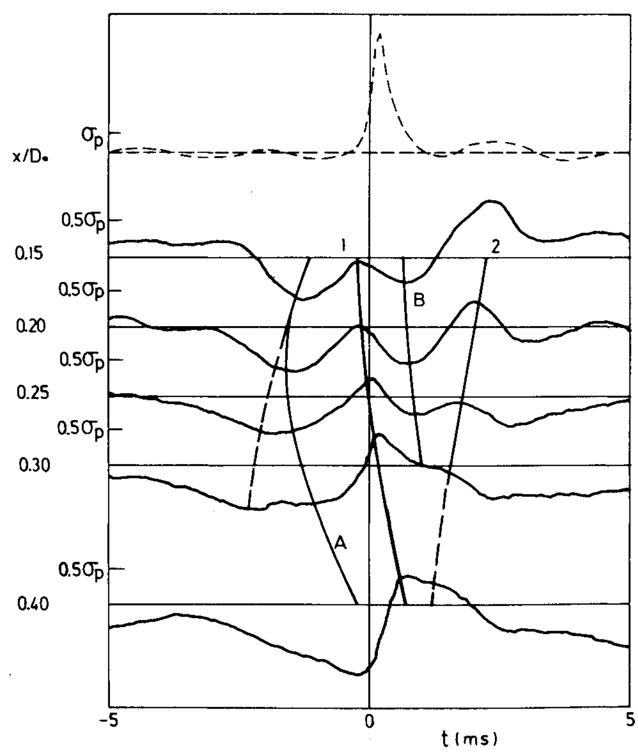


Fig. 2 Recovered pressure signals along jet central axis; $x/D_o < 0.4$. Topmost trace is the self-recovered signals of triggering microphone.

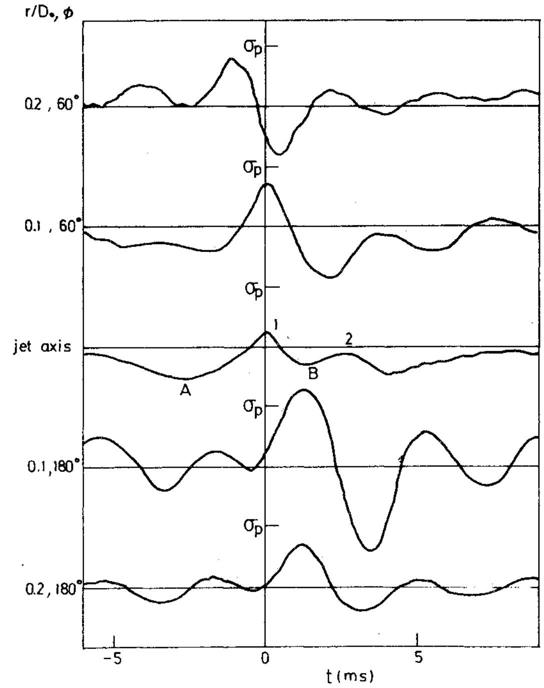


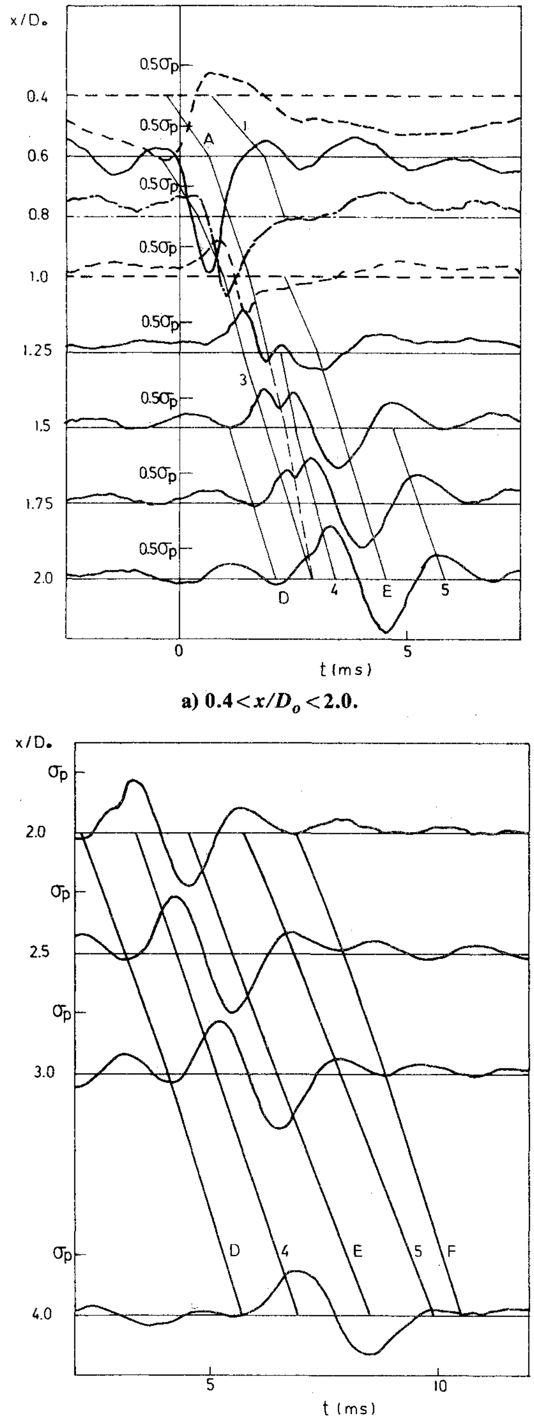
Fig. 3 Recovered pressure signals; $x/D_o = 0.25$.

downstream entrainment of the potential core fluid into the recirculating region. However, on the $\phi = 180$ deg plane, i.e., on the other side of the jet, the entrainment of fluid, represented by the path of the positive peaks, seems to occur in an upstream direction and toward the jet axis. Therefore, the shedding and the subsequent filling of fluid mass might not occur in a uniform front in the recirculating region.

In the recirculating region the flow may be primarily under the combined effect of the fluctuating pressure force and shearing force that occur in the inner mixing region. Any additional factors, such as the presence of other additional fluid and structure or azimuthal variation, may affect this basic pressure variation. With the shedding of a wake, the whole recirculating region may be in a transient state of partial vacuum (flow event A). The partial vacuum so established results in the inward entrainment of fluid from the inner mixing region into the recirculating region (flow event 1). Fluid masses aggregate to a certain degree and are then swept downstream by the action of the shearing force. The cycle is thus repeated.

The recovered signals at the jet central axis ($r/D_o = 0$) and downstream of the recirculating region are shown in Figs. 4a and b. Within the initial merging zone ($0.5 \leq x/D_o < 2$) flow event A is the most dominant (Fig. 4a). The time variation of the subatmospheric pressure of flow event A changes abruptly from a broad to a sharp peak, with the lowest pressure at $x/D_o = 0.6$. At $x/D_o = 0.6$ the estimated frequency of the positive peaks is about 500 Hz, which is slightly above that of the wake structure.

Flow event A is distinctly convecting downstream with a speed of about 0.7 $\bar{U}_0$. Hence this negative pressure can be associated with the passage of the wake vortex, which is convecting from the recirculating region.[10] As it convects downstream, its intensity weakens, and, downstream from $x/D_o = 1.5$, that is at the position where the potential core separating the inner and outer mixing regions disappears, it seems to be absorbed into other structures. At $x/D_o = 1.5$, flow events D, 4, and E appear. From the results of the signals recovered along the circumference of $r/D_o = 0.4$ which are not shown, the above flow events are associated with the coherent structures in the outer mixing region. Flow events D and E represent two outward-rotating vortices[10] and event 4 represents the braid convecting them.



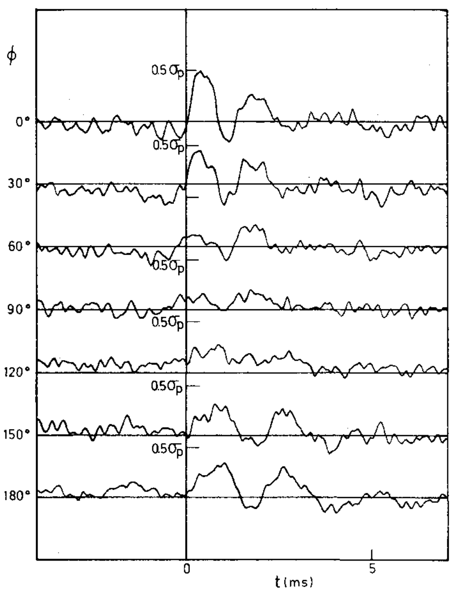
a) $0.4 < x/D_o < 2.0$.

b) $2.0 < x/D_o < 4.0$.

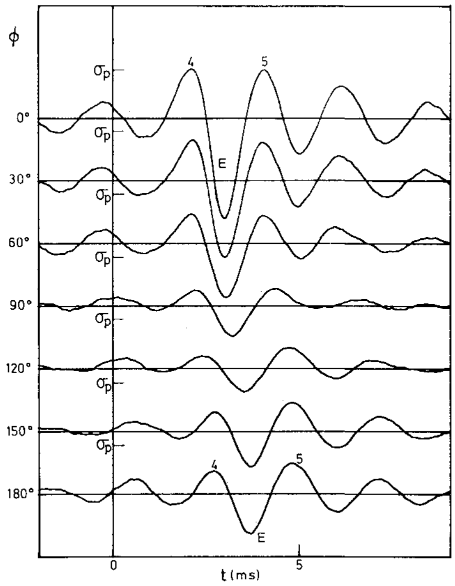
Fig. 4 Recovered pressure signals along jet central axis.

From the recovered signals, it is evident that there is an interaction between the wake vortex (event A) with the structures in the outer mixing region within the axial distance $1.25 < x/D_o < 2$. The fluid mass carried by the wake is first absorbed into the braid (event 4) connecting two successive vortices in the outer mixing region (events D and E). From the relative strength of the two events, it seems that the fluid absorbed into the braid is being entrained mainly into the trailing vortex E. After interaction, the vortices in the outer mixing region maintain their identity, at least up to $x/D_o = 4$ (Fig. 4b). It is also interesting to note that within the interaction region ($1.25 < x/D_o < 2$) the pressure intensity and covariance of the wake-induced vortices are at their maximum.[5]

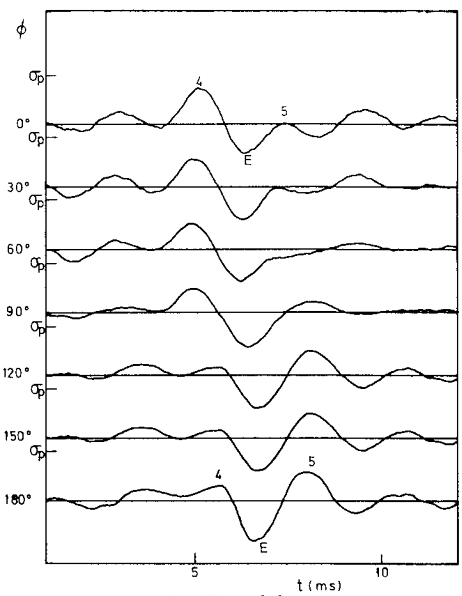
In order to understand the circumferential orientation of the structures in the outer mixing region, pressure traces were



a) $x/D_o = 0.5$.

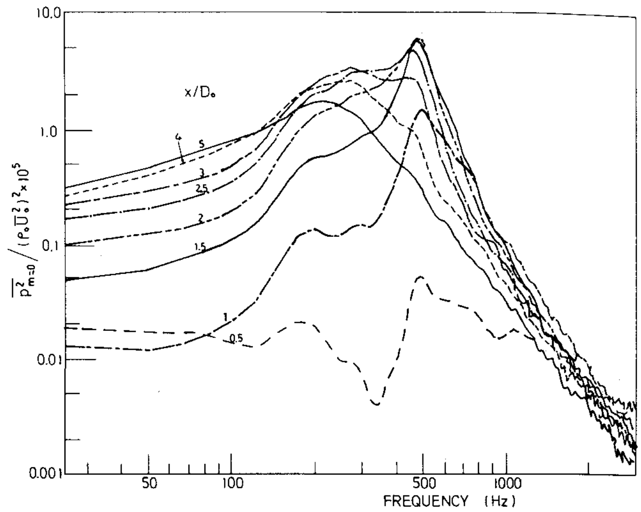


b) $x/D_o = 1.5$.

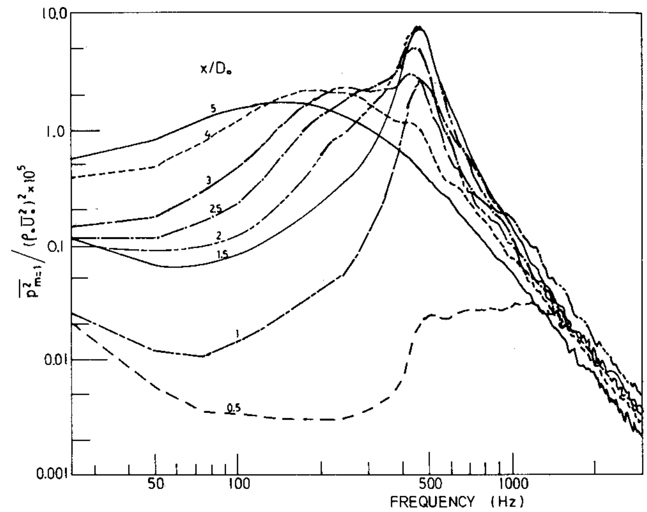


c) $x/D_o = 3.0$.

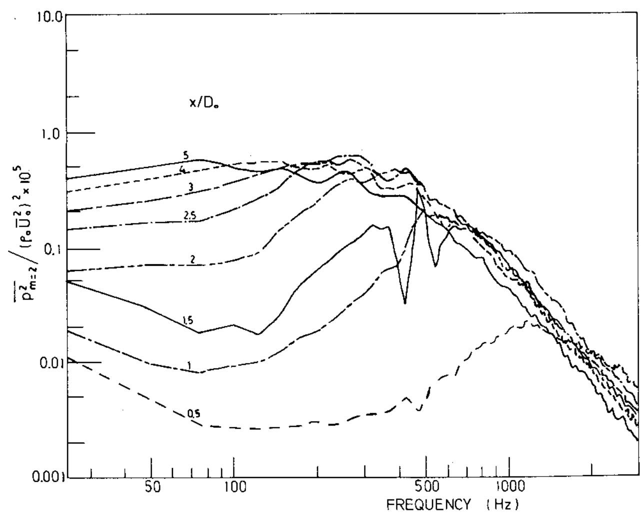
Fig. 5 Recovered pressure signals inside the outer mixing region ($r/D_o = 0.4$).



a) Axisymmetrical mode.



b) Mode 1.



c) Mode 2.

Fig. 6 Axial distribution of the modal pressure spectra in outer mixing region.

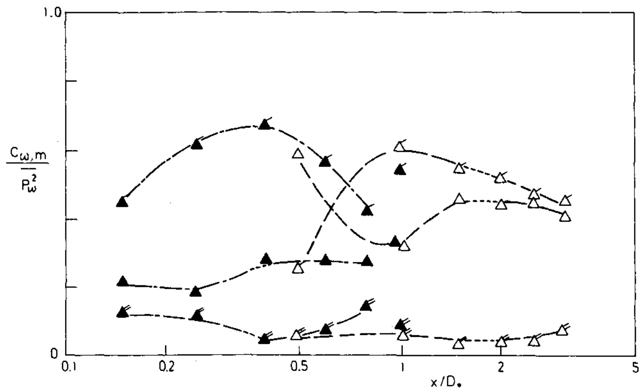


Fig. 7 Modal contributions of wake and wake induced vortices:—·—·—, wake; — — —, wake induced. Outer mixing region: △, mode 0; △, mode 1; △, mode 2. Inner mixing region: ▲, mode 0; ▲, mode 1; ▲, 2.

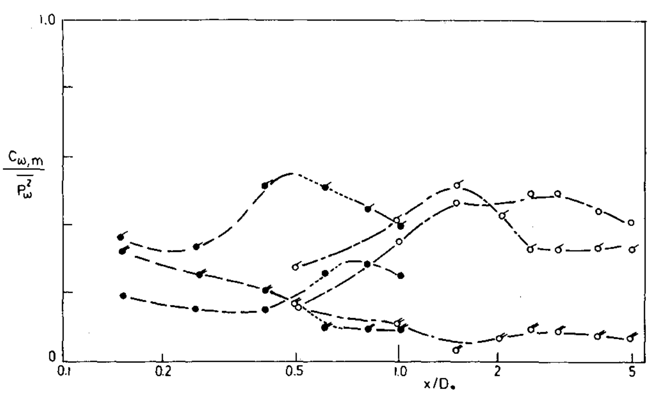


Fig. 8. Modal contributions of inner and outer jet vortices. — — —, inner jet vortices; —·—, outer jet vortices. Outer mixing region: open symbols; inner mixing region: closed symbols.

recovered at various azimuthal angles at $r/D_o = 0.4$ and are shown in Figs. 5a-c. At $x/D_o = 0.5$, the recovered signals are mostly of high-frequency components corresponding to the initial jet vortices in the outer shear layer. Near the triggering point, the shear layer is observed to roll up into a large-scale structure with a passage frequency approximately equal to that of the shedding wakes in the center (Fig. 5a). Pressure fluctuations associated with these structures on the two separate halves of the circumference are roughly 180 deg out of phase. At $x/D_o = 1.5$, the large-scale structure is well developed and its pressure fluctuation can be felt at the jet central axis (see Fig. 4). The phase shift between the two halves reduces to about 120 deg (Fig. 5b). Further downstream, at $x/D_o = 3.0$, the recovered pressure fluctuations are dominated by a component of lower passage frequency, and the phase shift is small (Fig. 5c). The significance of the above results will be discussed in a later section on modal analysis.

The modal analysis of the pressure fluctuations inside the outer and inner mixing region has been obtained. The axial distributions of the modal spectra for the axisymmetrical, first, and second modes inside the outer mixing region are shown in Figs. 6a, b, and c, respectively. The decomposition of the pressure spectrum into different modal spectra helps to identify different large-scale structures. Within the outer mixing region, the peaks at 200 and 280 Hz have contributions only in the axisymmetrical mode spectra. They are absent in spectra of higher modes. This suggests that they are very probably caused by the standing waves inside the plenum chamber. Besides the most dominant peak of 480 Hz of the wake-induced vortices, another broadband peak corresponding to

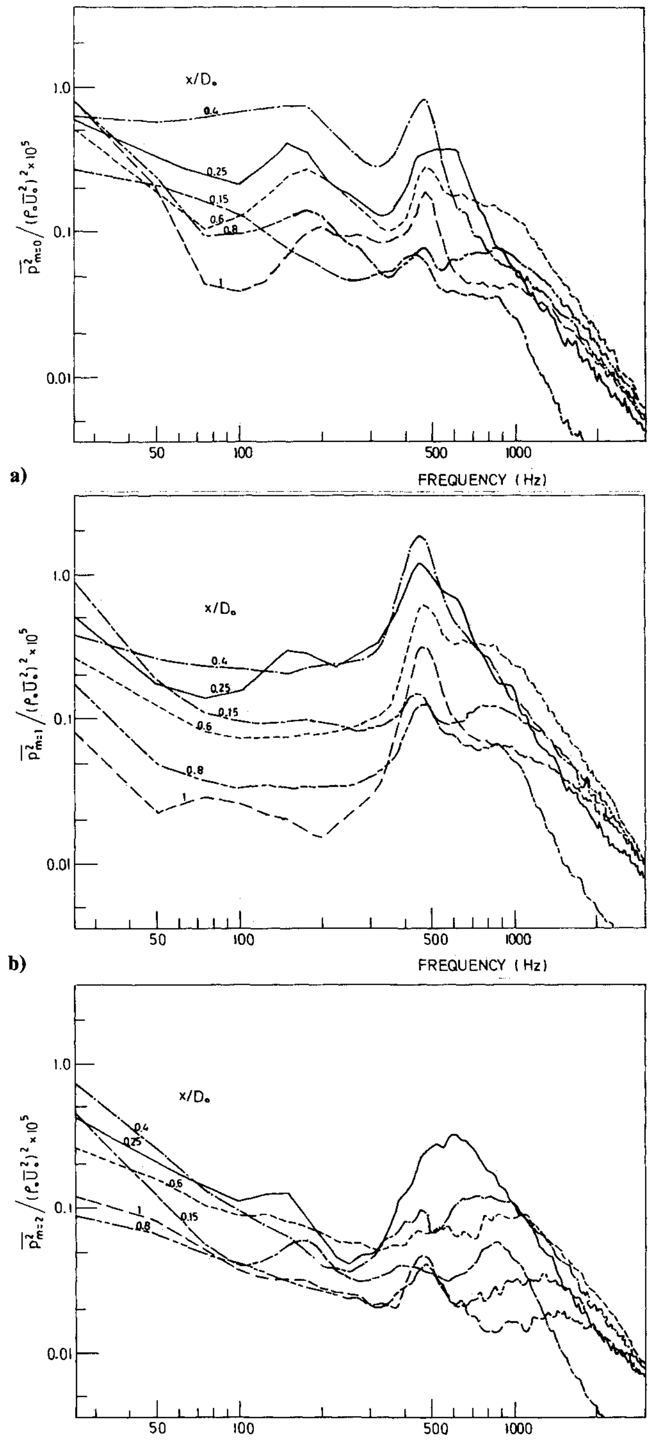


Fig. 9 Axial distribution of modal pressure spectra in the inner mixing region. a) Axisymmetrical mode. b) Mode 1. c) Mode 2.

the outer jet vortices can be located from the axisymmetrical mode and mode 1 spectra at all streamwise stations. The modal constituents of the wake-induced vortices and the outer jet vortices are shown in Figs. 7 and 8, respectively. While these latter figures help to show the development of different modes downstream, the modal spectra in Fig. 6 give a more complete picture at the whole frequency range. At $x/D_o = 0.5$, the wake-induced vortices are not well developed and the pressure fluctuations at 480 Hz suffer significantly from the contributions from the broadband jet vortices. The observed large contribution from the axisymmetrical mode does not follow the trend downstream (Fig. 7), nor does it agree with the antiphase relationship observed in the earlier circumferential time domain analyses (Fig. 5a). The disagreement may be that the modal expansion technique of representing coherent structures is a straightforward statistical analysis over the whole frequency range, whereas the conditional sampling technique selects a dominant structure or event in the flow. Hence, while the time domain analyses show alternating wake-induced vortices at $x/D_o = 0.5$, the effects of other structures and background turbulence smear its observed modal distribution. Further downstream, when the wake-induced vortices become well-developed, their modal contribution agrees with the recovered time traces, such as at $x/D_o = 1.5$ (compare Figs. 5b and 7). At $x/D_o = 3.0$ the wake-induced vortices start to decay and the outer jet vortices become more dominant (Fig. 6). The dominance of its axisymmetrical mode (Fig. 8) accounts for the observed lower passage frequency and in-phase characteristics of the circumferential recovered pressure traces (Fig. 5c).

The modal spectra obtained inside the inner mixing region ($r/D_o = 0.2$) are shown in Figs. 9a-c. Three coherent structures can be identified: 1) the 480 Hz component ($fD_i/\bar{U}_0 = 0.27$, $fD_o/\bar{U}_0 = 0.59$), caused very probably by the shedding wake from the blunt interface; 2) the lower frequency component around 150 Hz, which may be due to the standing recirculating vortex behind the interface; and 3) the high-frequency broadband peak, which is thought to be due to a kind of jet vortex in the inner shear layer (termed the inner jet vortices). The modal contributions of the wake and inner jet vortices at their peak frequencies are also shown in Figs. 7 and 8, respectively. The dominating first-mode characteristic of the shedding wake is consistent with that of the wake of a circular disk.[13] The similar antiphase relationship found in the wake-induced vortices supports the proposal of its origin as an excitation of the outer shear layer by the disturbances associated with the shedding wakes.

The inner jet vortices have a first-mode constituent that is more dominant than that from the axisymmetrical mode. Further, for $x/D_o < 0.5$ the second-mode constituent is even higher than that of the axisymmetrical mode. The dominance of the first- and second-mode constituents suggests that the structure of the inner jet vortices is different from that of a toroidal vortex. A circumferentially fragmented multilobe structure may be a slightly better description. The reason for that may be due to the influence of the shedding of the fluid mass from the recirculating region in a nonuniform front, as discussed earlier. However, further investigation will be required for better understanding of its detailed structure.

Conclusions

The present study of the pressure fluctuations within the initial region of the basic annular jet indicates the complexity of the flow structures within the jet. At the present diameter ratio the flow structure set up behind the interface is the dominant factor, affecting not only the flow characteristics in the inner central region downstream but also those in the outer region of the jet. Because of the entrainment of the annular jet, the degree of the subatmospheric pressure set up behind the interface governs the characteristics of the inner jet vortices. These vortices are generally convecting downstream and have inward movement toward the jet central axis. However, there are occasions when they convect upstream toward the interface at the nozzle exit.

Because of the close relationship of the flow structures in the inner and outer regions of the jet, their modal characteristics are also closely related. The dominance of the first-mode constituent of the wake vortices is reflected in the wake-induced vortices after their formation and convection downstream.

Acknowledgments

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