Investigation of Flow Structures of a Basic Annular Jet

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A conditional sampling study of the pressure fluctuations in the mixing regions of basic annular jet is presented. The wake structures shed from the recirculating region behind the central body in the inner mixing region together with the wake-induced structures in the outer mixing region are satisfactorily educed from the recovered pressure signals. The study provides further evidence that the wake-induced structures are induced by the shedding wakes. Information is also given on the relative positions of different flow structures and their possible interactions.

Introduction

COHERENT structures in the planar and axisymmetric mixing layers of a circular jet have been studied extensively. The coherent structures are widely believed to play important roles in turbulent stresses, production, mixing, and noise generation. The conditional sampling technique has emerged as useful tool to study and educe the coherent structures.[1] Controlled perturbation of the shear layer, usually by means of acoustic excitation, is again a common technique in organizing the coherent structures so they can be easily extracted.[2]

In a basic annular jet in which the central body has a blunt downstream end or interface, a region of recirculating flow is found attached to the interface. Chan and Ko[3] have shown that periodic wake structures are shed from the recirculating region. Ko and Chan[4] further detected the presence of another train of coherent structures in the outer mixing region, which has a quasipassing frequency the same as the wake-shedding frequency. This train of wake-induced structures was believed to be induced by excitation of the outer shear layer due to the disturbances associated with the wake structures shedding from the interface. Therefore, the basic annular jet allows an alternative mode of shear-layer excitation to the acoustic excitation in the circular jets. Thus, it is interesting to investigate in greater depth the excitation mechanism and the evolution of the wake-induced and wake structures.

Using the mode expansion scheme, Ko and Lam[5,6] showed that both the wake structures in the inner mixing region and the wake-induced structures in the outer mixing region contain a dominating first azimuthal mode constituent. Ko and Lam[6] also reported recovered pressure signals along the jet central axis. It seemed that the wake and wake-induced structures do not lie in the same front around the axial distance of 1 o.d. downstream.

Further to the investigation reported[6], additional and more detailed results of the conditionally sampled pressure fluctuations are reported. The signals were recovered with reference to a prescribed phase in the shedding cycle of the wake structures. It is hoped that a more detailed and better understanding of the wakes and of the structures in the outer shear layer is attained. The relative orientation and the interaction of the wake and wake-induced structures are also obtained.

Experimental Procedures

The measurements were obtained in a basic annular jet with an outer diameter D_o of 61.5 mm, an inner diameter D_i of 28.3 mm, and a diameter ratio D_i/D_o of 0.46. The exit jet velocity U_0 was 50 m/s, giving a Reynolds number U_0D_o/ν of 2×10^5. The design and geometry of the annular jet have been reported in Refs. 3-6. The exit conditions of both the outer and inner shear layers were laminar. Static pressure fluctuations were measured with the Bruel and Kjaer ⅛-in. condenser microphones fitted with standard nosecones. The triggering microphone was placed at a fixed location on the edge of the recirculating region at $x/D_o=0.4$, $r/D_o=0.2$, and $\phi=0$ deg. Figure 1a shows the pressure spectra at that location, and Fig. 1b shows an example of the time history. It can be observed that the triggering pressure signal is greatly dominated by the contribution of the shedding wakes at a frequency of about 450 Hz or a quasiperiod of about 2.2 ms. Judging from the time history (Fig. 1b), the threshold triggering level of $+2\sigma_p$ was chosen where σ_p is the rms value of the pressure signal.

The recovery microphone was placed at various locations to enduce the signatures of the large-scale coherent structures. The most elaborate measurements were performed with the recovery microphone placed at an x-r grid on the $\phi=60$ and 180 deg planes. The adoption of the former plane instead of the $\phi=0$ deg plane was due to the physical interface of the two microphones. Although the experimental uncertainty due to the size of the microphone has been discussed in Ref. 6, the question of probe interference is still a matter of controversy of major concern to the readers. Therefore, it was decided to determine its effect on the strategic results of the present investigation with a control experiment. The outcome of the control experiment, which will be described later, concluded that although the probe interference is not negligible, it did not preclude the major interpretations of the present study.

Conditional samplings were performed on the real-time Hewlett-Packard Structural Dynamic Analyzer Model HP5423A. Whenever the triggering signal rose above the threshold level of $+2\delta_p$ and had a positive slope, both signals of the two microphones were sampled with appropriate pre- and postdelay periods. The moving ensemble average was currently displayed on the analyzer until covergence of the recovered time trace was achieved. The final ensemble size was typically 1000-1500.

Results and Discussions

Outer Mixing Region

The radial location of $r/D_o=0.4$ was chosen as the measuring location in the outer mixing region.[5] The educed pressure traces $p_R(t)$ at successive axial locations recovered at $\phi=0$ deg, i.e., on the same azimuthal side of the triggering wake struc-

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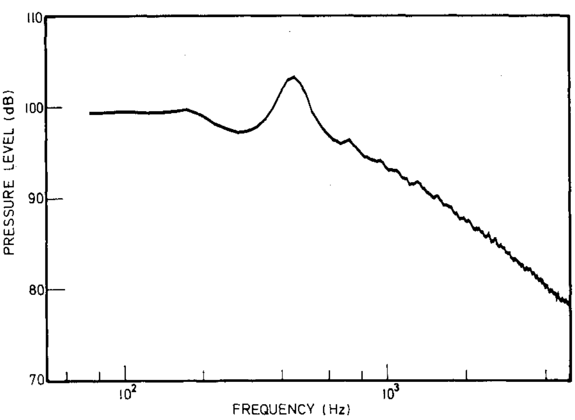
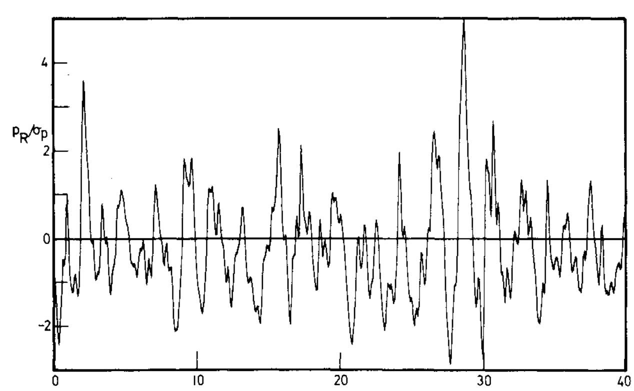
tures, are shown in Fig. 2a. Lau and Fisher[1] suggested that the recovered pressure trough is associated with the passage of a covecting well-organized vortex structure. Therefore, the largest pressure troughs at different axial locations are most probably due to the passage of a strongly educed wake-induced structure in the outer mixing region at $\phi = 0$ deg. This structure is denoted as OA, and its convection path is marked with a solid line in Fig. 2a. Pressure signals are also recovered at $\phi = 180$ deg along the same axial locations. The educed traces, $p_R(t)$ shown in Fig. 2b, also show the passage of a wake-induced structure OB at $\phi = 180$ deg. The paths of OA and OB are crossplotted in Fig. 2. It is then evident that at $x/D_o < 1.5$, OA and OB are nearly in antiphase. Further downstream their phase difference becomes smaller, and at $x/D_o = 4$ they become almost in-phase. The modal analysis of Ko and Lam[5] showed that, for the wake-induced structures, the first azimuthal mode is the most dominant at the more upstream region of $x/D_o < 2$ and at $x/D_o > 2$ the first mode constituent is only slightly higher than that of the axisymmetric zero mode.

Regarding the recovered magnitudes, the pressure signals are best educed in the axial position of $x/D_o = 1$–2. Earlier investigations showed that the wake-induced structures reach their maximum intensity in this axial region. Moreover, the recovered traces in this region show regular periodicity at the wake-shedding period. Further downstream at $x/D_o > 2.5$, the recovered magnitudes drop and the traces show a tendency toward lower frequency. The decay of the wake-induced structures and the dominance of the natural jet column mode coherent structures[5] may be responsible for this change of features of the recovered pressure traces, In the initial outer shear layer at $x/D_o = 0.5$, high-frequency initial vortices are educed in the pressure traces (Fig. 2). The recovered magnitudes are much lower than those at the more downstream locations, suggesting that not all of the initial rolled-up vortices are excited by the shedding wakes in the central region. However, around the occurrence of the wake-induced structures OA and OB, large-scale pressure fluctuations of lower frequency are recovered. The large-scale pressure crests and troughs appear to be formed by the merging of a number of high-frequency crests and troughs due to the initial jet vortices. Hence, the possibility arises that a wake-induced structure may be formed from the merging of a number of initial jet vortices, which are under the excitation of

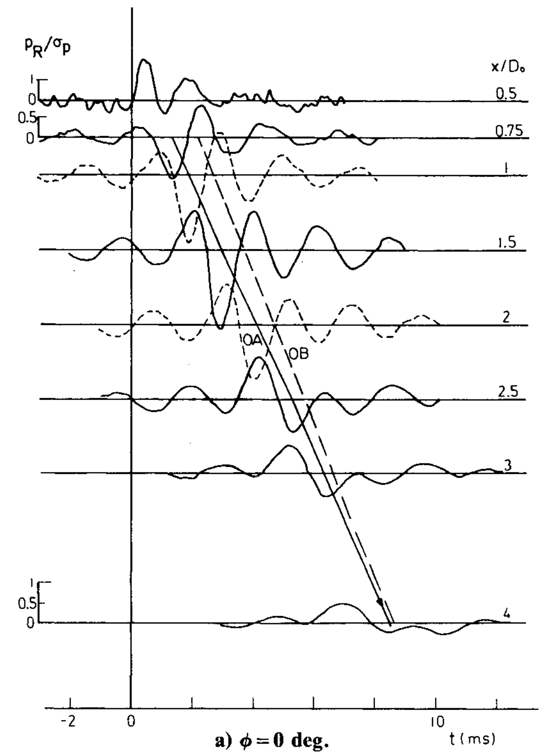


a) Autopower spectrum.

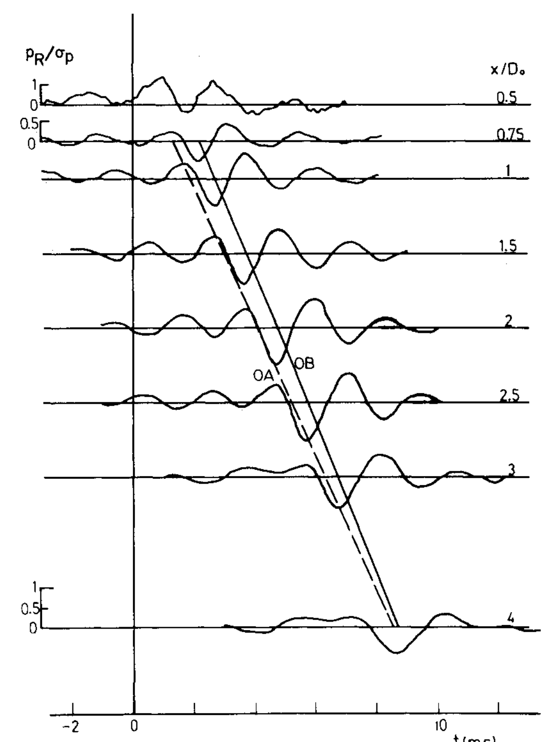


b) Time history.

Fig. 1 Triggering pressure signal at $x/D_o = 0.4$, $r/D_o = 0.2$, and $\phi = 0$ deg.



a) $\phi = 0$ deg.



b) $\phi = 180$ deg.

Fig. 2 Recovered pressure traces in the outer mixing region at $r/D_o = 0.4$

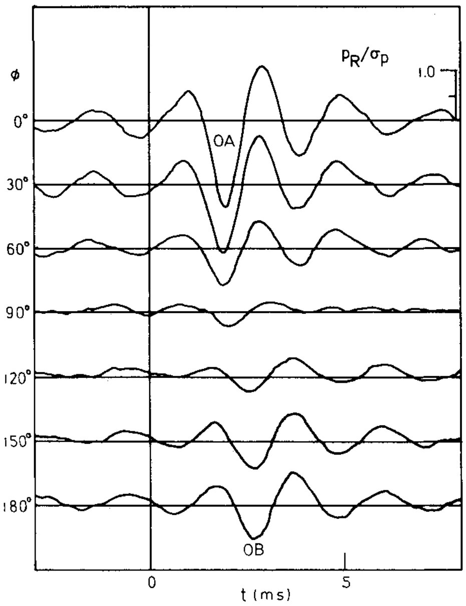
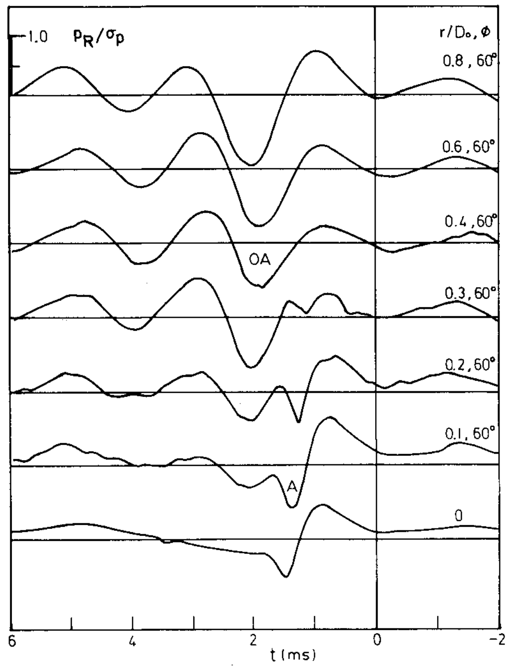
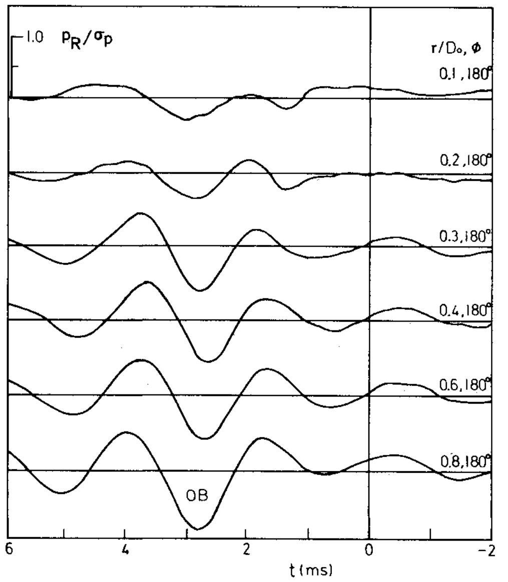


Fig. 3 Recovered pressure traces at different azimuthal angles in the outer mixing region: $x/D_o = 1$ and $r/D_o = 0.4$.



a) $\phi = 60$-deg plane.



b) $\phi = 180$-deg plane.

Fig. 4 Recovered pressure traces at different radial locations: $x/D_o = 1$.

the disturbances of the shedding wake structure. The merging of a number of vortices has been reported by Ho and Huang[7] in the subharmonic forcing of plane mixing layers and by Ho and Nosseir[8] in an impinging jet at high subsonic Mach numbers. At this stage, it is not known whether a "collective interaction," which is responsible for the above phenomena, can be triggered by the disturbances of the shedding wake. Returning to the recovered traces $x/D_o = 0.5$, the time intervals between the peaks which are not of the large-scale fluctuations vary mainly from 0.4 to 0.7 ms. These correspond to the quasifrequencies of 1.4 to 2.5 kHz, which agree with the spectral frequency of the broadband peak found in the pressure spectrum due to the initial jet vortices.[5] On the other hand, the frequency of the large-scale fluctuations is estimated to be 600-800 Hz. Hence, the formation of the wake-induced structures at 460 Hz is not yet completed at $x/D_o = 0.5$. The formation is completed at $x/D_o = 0.75$.

The convection velocity of the wake-induced structures can be estimated from the paths of OA and OB in Fig. 2. OA and OB are seen to convect at slightly different velocities. Their average convection velocity is 29.8 m/s or $0.60U_0$.

The recovered pressure traces at different azimuthal angles on the circle of $r/D_o = 0.4$ at $x/D_o = 1$ are shown in Fig. 3. It is evident that OA at $\phi = 0$ deg and OB at $\phi = 180$ deg are not sections of a tilted toroidal vortical structure. On the contrary, the wake-induced structures seem to be of the form of a "spotty" vortical puff spanning about one-half the circumference, with successive wake-induced structures in alternating locations.

Radial Variations

Figure 3 shows that the pressure traces educed on $\phi < 90$ deg are nearly identical in phase. Hence, pressure traces recovered on the $\phi = 60$-deg plane are used to describe the flow structures centered at $\phi = 0$ deg. Figure 4a and 4b show the pressure traces recovered at different radial locations on the $\phi = 60$- and 180-deg planes, respectively. The time t relative to the triggering instant is shown decreasing to the right so as to represent a streamwise direction to the right by Taylor hypothesis.[9] In addition to the wake-induced structures OA and OB on two sides of the outer mixing region, a wake structure A is recovered in the inner mixing region ($r/D_o \simeq 0.1$). The education results of Ko and Lam[6] on the jet central axis have shown that this wake structure convects from the recirculation region to an axial distance of about $x/D_o = 2$, beyond which it decays.

From the recovered pressure traces, the contour map of the recovered pressure intensity $p_R/\rho_0 U_0^2$ is plotted in Fig. 5. The wake-induced structures OA and OB are marked by regions of negative pressure centered at $r/D_o \simeq 0.4$. In addition of OA and OB, a number of other wake-induced structures are also recovered. It is clear from the contour map that the two trains of wake-induced structures at $\theta = 60$ and 180 deg are orientated in a neat alternating pattern at this axial location. The region of closed isocontours of negative pressure centered at $r/D_o \simeq 0.1$ and $t \simeq 1.3$ ms is the wake structure A. It is observed from this contour map that the location of OA in the outer mixing region is lagging behind that of A in the inner mixing region.

The recovered pressure traces at a location further downstream at $x/D_o = 1.5$ are shown in Fig. 6. At $r/D_o < 0.2$

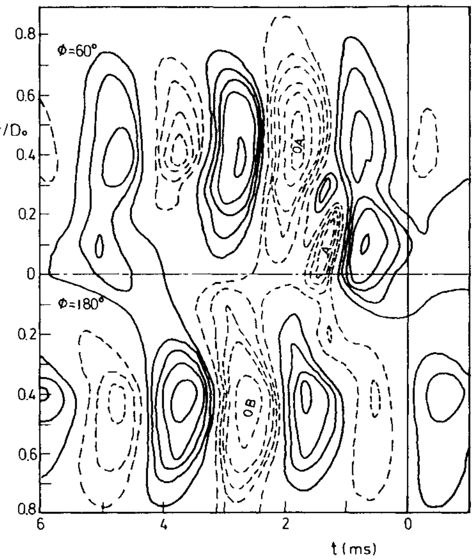


Fig. 5 Contour map of recovered pressure intensity $p_R/\rho_0\bar{U}_0^2$ at $x/D_o=1$. Contour levels are ±0.2, ±0.4, ±0.6, ±0.8, ±1.2, and ±1.6%.

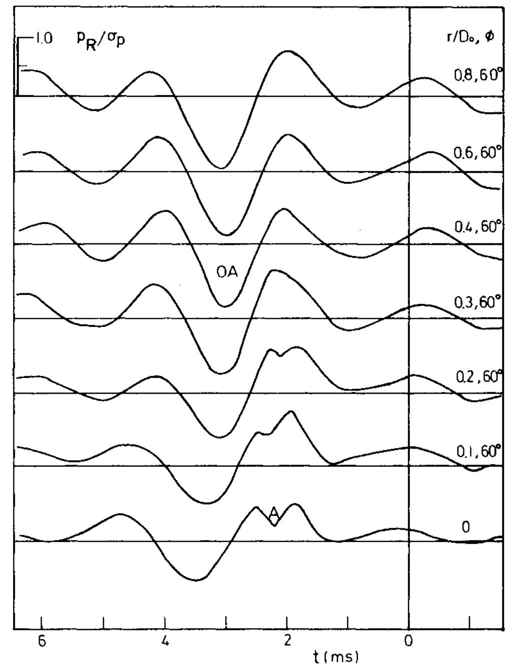
and $\phi=60$ deg, the wake structure A is found to be decaying. The contour map of $p_R/\rho_0\,U_0^2$ constructed from the traces is shown in Fig. 7 for $\phi=60$ deg. It can be observed that the negative regions corresponding to the educed wake-induced structures increase in size, while the negative region corresponding to wake structure A in Fig. 5 disappears and becomes instead an indentation to the positive region of p_R at approximately $t\simeq2.2$ ms. As the regions of negative pressure are taken to be due to the passage of large-scale vortical structure, the regions of positive pressure thus represent the braid or saddle region connecting these structures. Hussain[10] and Cantwell and Coles[11] both stressed the roles of the saddle region in the dynamics of coherent structures. The saddle region or the braid joining two coherent structures was suggested to play an important role in inducing entrainment and producing incoherent turbulence, which is then transported away from the saddle to feed the large-scale coherent structures. Therefore, the contour map of Fig. 7 seems to suggest that the fluid masses and the fine-scale turbulence, which are originally associated with wake structure A, may be entrained into the braid region preceding OA. Previous investigations[4-6] showed that the wake-induced structures reach maximum intensity around $x/D_o\simeq1.7$. It is not certain whether there is a connection between the maximum intensity with the aboveproposed entrainment of the decaying wake structure.

From the recovered traces in Fig. 5, OA and OB are also out of phase, but the phase difference is smaller than that at $x/D_o=1$ (Fig. 4).

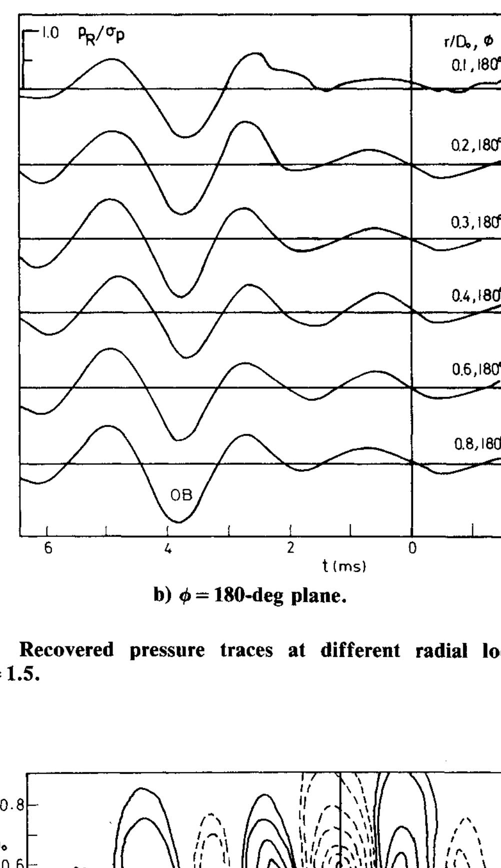
From $x/D_o=1$ to 1.5, the convection velocity of wake structure A, which is defined by the regions of negative recovered pressure at $r/D_o=0.1$ in the contour maps or by the negative pressure trough or indentation in the recovered traces, is estimated to be approximately 37.1 m/s or $0.74U_0$. This is higher than the estimated convection velocity of the wake-induced structures in the outer mixing region.

Time Evolution on the $\phi=60$ and 180-deg Planes

Other than $r/D_o=0.4$ in the previous section and the jet central axis,[6] pressure fluctuations have been educed along other radial locations at successive axial stations on the $\phi=60$- and 180-deg planes. As shown in Fig. 2, the downstream convections of the negative (or positive) peaks in the educed time traces can be followed by their axial variations. The axial locations of these educed "fronts" at any time t relative to the triggering instant can then be estimated by interpolating their convections between two axial measuring stations.[12] In this way,



a) $\phi=60$-deg plane.



b) $\phi=180$-deg plane.

Fig. 6 Recovered pressure traces at different radial locations: $x/D_o=1.5$.

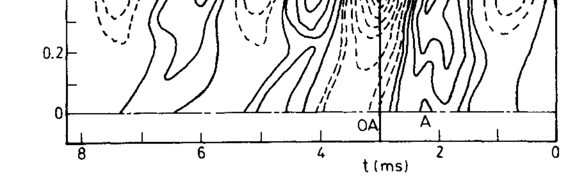


Fig. 7 Contour map of recovered pressure intensity $p_R/\rho_0\bar{U}_0^2$ at $x/D_o=1.5$. Contour levels are ±0.25, ±0.5, ±1, ±1.5, ±2, −2.5, −3, and −3.5%.

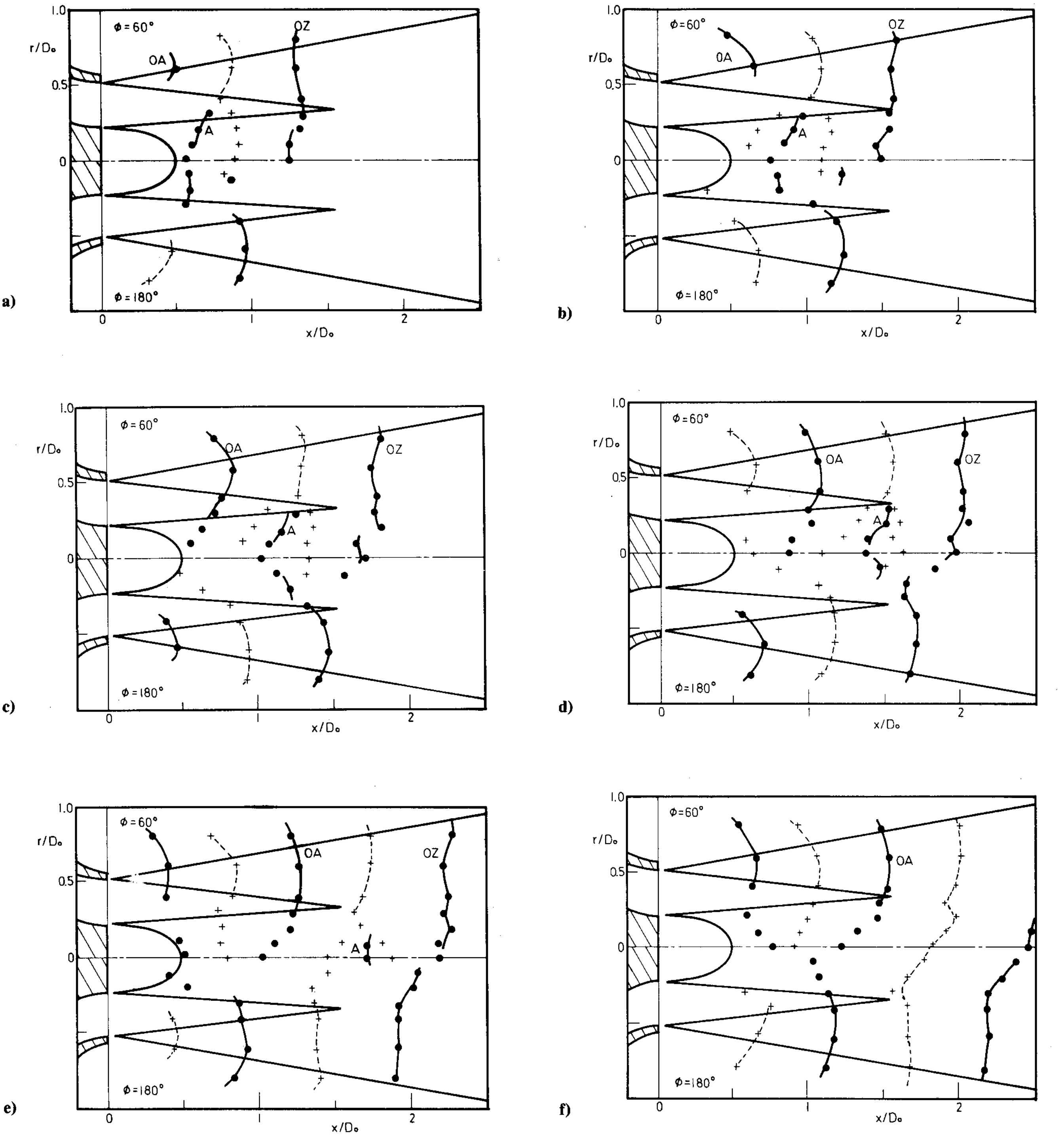


Fig. 8 Recovered p_R fronts on the $\phi = 60$- and 180-deg plane: o ---- o , negative fronts; + ---- +, positive fronts. a) $t = 0.5$ ms, b) $t = 1$ ms, c) $t = 1.5$ ms, d) $t = 2$ ms, e) $t = 2.5$ ms, and f) $t = 3$ ms.

the spatial locations of identified fronts of educed flow events on the two azimuthal planes are plotted in Figs. 8a–8f for $t = 0.5$, 1, 1.5, 2, 2.5, and 3 ms, respectively. In these figures, the solid symbols and lines denote the approximate locations of negative fronts of p_R while the plus (+) symbol and dotted lines denote those of positive fronts. Following this convection, the fronts of negative p_R are interpreted as the centers of the flow structures, and the fronts of positive p_R give the approximate locations of the braid regions between the flow structures.

At $t = 0.5$ ms (Fig. 8a), the wake structure A has already been shed from the recirculating region and convects to $x/D_o \simeq 0.7$. The wake-induced structure OA in the outer mixing region is orientated in an approximate staggered position with A. When A convects to $x/D_o \simeq 1$ at $t = 1$ ms (Fig. 8b), its spatial location is between two wake-induced structures, namely OA and the one before OA, namely OZ. As A convects near to the top of the potential core at $t = 1.5$ ms (Fig. 8c), its location is approximately on the inside of the braid region between OA and OZ. When the potential core ends (Figs. 8d–8f) wake structure A gradually loses its own identity of p_R front from $t = 2$–3 ms. The decay of A seems to be related to the activity of the braid region preceding OA.

For the flow events of the $\phi = 180$-deg plane, the wake-induced structures are out of phase with those on the $\phi = 60$-deg plane such as OB with OA in Figs. 8c–8f. The phase

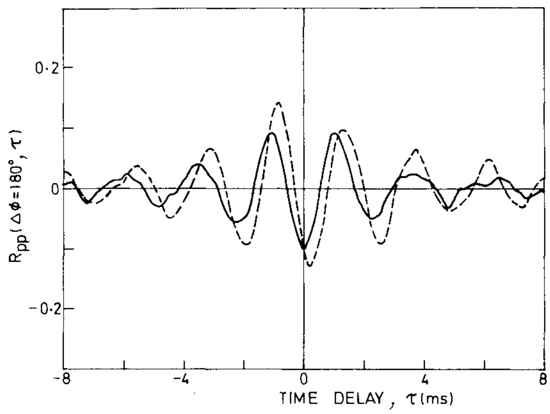


Fig. 9 Cross-correlation coefficient between signals across the jet ($x/D_o = 1$, $r/D_o = 0.4$): —, upstream probe absent; ----, present.

difference between the wake-induced structures on the opposite sides of the jet is observed to become smaller at increasing axial distances at $x/D_o > 2$.

It is also evident from Figs. 8a–8f that the wake structures in the inner mixing region convect downstream with a convection velocity higher than that of the wake-induced structures in the outer mixing region.

Probe Interference

From the foregoing discussions, it is clear that one of the most important results is that the pressure signals are out of phase on the opposite sides of the jet. Yet questions of probe interference remains. Does the upstream triggering microphone account for any of the observed phenomena downstream? If so, to what extent? To get an estimate of the influence, a simple control experiment was performed in which the cross-correlation coefficient between the two microphone signals at $\phi = 0$ and 180 deg ($x/D_o = 1$ and $r/D_o = 0.4$) was measured in two situations with the upstream triggering microphone present and absent, respectively. The comparison is shown in Fig. 9. Consistent with the modal analysis results of Refs. 5 and 6, the signals across the jet are out of phase. The fact that this antiphase character is observed even when the upstream probe is present firmly supports that the main qualitative deduction from the present investigation has not been biased by any probe interference. Actually, it is obvious from Fig. 9 that the presence of the upstream probe seems to impair the originally distinguishing antiphase character of the large-scale structures. This may be due to the introduction of background turbulence and the diffraction and radiation of the sound field by the upstream microphone. The noise radiated and scattered by the upstream probe may also be responsible for the slightly higher cross-correlation coefficient observed for the two downstream locations. As for the pressure intensity, a decrease by 0.9 dB was observed at $\phi = 0$ deg ($x/D_o = 1$ and $r/D_o = 0.4$) when the triggering probe was in place. On the other hand, the signal at $\phi = 180$ deg experienced 1.3-dB increase. However, the frequency distribution of the spectral densities remains basically identical.

Conclusions

A conditional sampling study of the pressure fluctuations in a basic annular jet was presented. It was demonstrated that the pressure fluctuations can detect the passages of large-scale structures. Results in the initial outer mixing region ($x/D_o = 0.5$ and 0.75) suggest that some of the initial jet vortices rolled up in the shear layer are induced to merge together into the wake-induced structures under the excitation of the disturbances due to the shedding of the wake structures from the interface. The wake-induced structures are not in toroidal form. The results suggest that their occurrences are spanning about one-half the circumference of the outer mixing region, with successive alternating structures and the plane of symmetry changing randomly in time to assume statistic axisymmetry.

Although the wake-induced structures are induced by the shedding wakes, the former structures in the outer mixing region are found to lie in a staggered position with the wake structures in the inner mixing region. The two structures are also found to convect downstream at different speeds. The convection velocity of the wake-induced structures is about $0.6U_0$ while that of the wake structures is about $0.7U_0$. At $x/D_o = 1.5$, the wake structures decay and their positions are in the inside of the braid regions between the successive wake-induced structures in the outer mixing region. Around the same axial location, the wake-induced structures reach their maximum intensity.

Acknowledgment

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