J. Fluid Mech. (1977), *vol.* 82, *part* 2, *pp.* 273–287
Printed in Great Britain

The initial region of subsonic coaxial jets. Part 2

By A. S. H. KWAN AND N. W. M. KO
Department of Mechanical Engineering, University of Hong Kong

(Received 13 December 1976)

Earlier investigations by the authors have suggested that coherent structures, in the form of two different arrays of vortices, exist in the initial region of coaxial jets. The present investigation was aimed at obtaining further information on the characteristics of the vortices in coaxial jets. Single- and two-point correlation covariance measurements of the fluctuating pressure and the axial and radial velocity fluctuations have been made in the initial region of coaxial jets. Detailed analysis of the correlograms indicates the combined effect of the two vortex trains on the correlograms. Further, the analysis enables the phase relationship between the pressure and axial and radial velocity fluctuations to be obtained. From the correlation results the phase properties obtained within the whole initial region of coaxial jets are found to agree with the results for single jets. This good agreement supports the formally suggested simple approach to the understanding of the complicated flow in coaxial jets.

1. Introduction

Earlier work of the authors (Ko & Kwan 1974, 1976; Kwan & Ko 1976) indicated that the initial region of a coaxial jet can be divided into three zones (figure 1). The initial-merging zone extends from the jet exit plane to the tip of the secondary potential core. The fully merged zone starts at about the point where the two jets have merged completely and the coaxial jet behaves like a single jet. The intermediate zone is found between the initial-merging and fully merged zone. The experimental results for the distributions of the mean velocity and turbulence intensity in different zones of coaxial jets of different velocity ratios indicated that the complicated flow structure of the coaxial jets could be very simply related to, and described by, the much simpler structure of single jets.

On the basis of the recent observations of coherent structures in the mixing region of single jets described by Crow & Champagne (1971), Lau, Fisher & Fuchs (1972), Laufer, Kaplan & Chu (1974), Winant & Browand (1974), Chan (1974), Lau & Fisher (1975) and Michalke & Fuchs (1975), the present authors have proposed a simple model of the coherent structures in coaxial jets (Ko & Kwan 1976; Kwan & Ko 1976). Basically, they described two arrays of vortex rings which were found in both the primary and the secondary mixing region of coaxial jets. The presence of these vortices are supported by the experimental results presented in the above work.

The high frequency fluctuations observed in the primary mixing region were induced by the primary vortices which were generated there. These vortices had an axial separation of about $1{\cdot}2D_i$ and were convected downstream with a velocity of $(\overline{U}_c)_i = 0{\cdot}6(\overline{U}_i - \overline{U}_o) + \overline{U}_o$. The low frequency fluctuations, however, were induced by

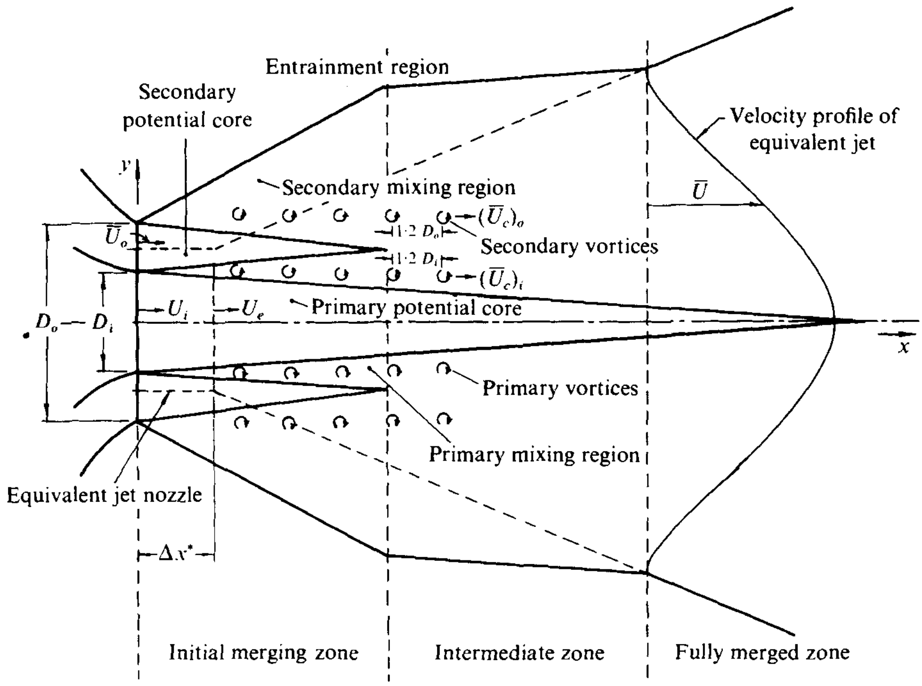

FIGURE 1. The initial region of a coaxial jet.

the secondary vortices which were generated in the secondary mixing region. They had an axial separation of about $1{\cdot}2D_o$ and were convected downstream with a velocity of $(\overline{U}_c)_o = 0{\cdot}6\overline{U}_o$.

In the intermediate zone the growth or decay of these two types of vortices depend largely on the deviation of the modes of the vortices from the preferred ones. Continuous growth was observed when the mode was about the same as the preferred one. This concept of the preferred mode has also been justified by the experimental results.

A similar model has been developed by Lau (1971) to provide a simplified picture of the structure of the initial region of a single jet. The vortex model proposed by Lau *et al.* (1972) and the 'extended' vortex model proposed by Lau & Fisher (1975) explained the phase relationships between the fluctuating pressure and the axial and radial velocity fluctuations in the potential core and in the entrainment region, the occurrence of the large positive and negative spikes in the time-history traces of the hot-wire signals and the existence of a mean Reynolds shear stress in the mixing layer. The vortex model comprised the basic vortices in the mixing layer. The leading edge of each basic vortex induced an outflow of high velocity fluid from the potential-core side of the mixing region across into the low velocity region. Similarly, the low velocity fluid was transported radially inwards towards the potential core by the trailing edge of each vortex.

Since previous studies by the authors (Ko & Kwan 1976; Kwan & Ko 1976) have already indicated the possibility of a regular pattern consisting essentially of two trains of axially spaced vortices, the present investigation concentrated on the study of the phase relationships between the fluctuating pressure and the axial and radial velocity fluctuations in the initial region of coaxial jets. Further, it was intended to

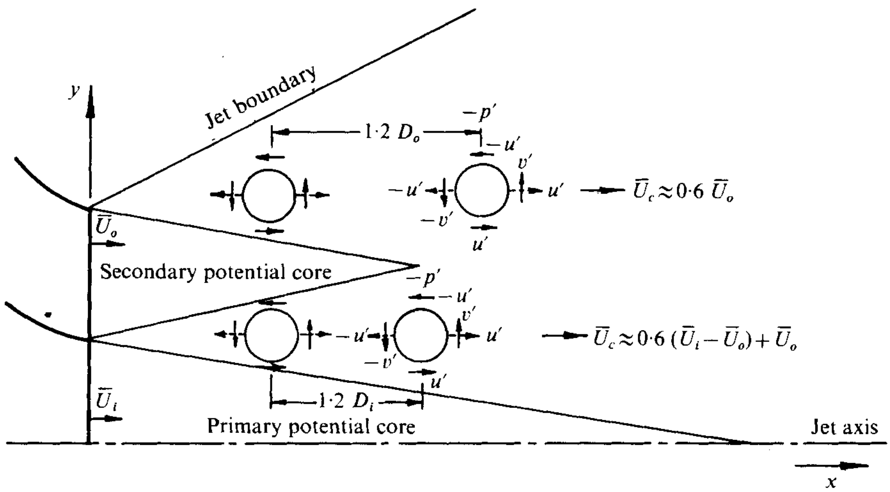

FIGURE 2. The model for coaxial jets. ←—, due to basic vortex; ←- - -, due to nonlinear mass transfer.

provide additional information on the structure of the vortices in coaxial jets so that they could be compared with the vortices observed in single jets.

2. The model

The simple model proposed for coaxial jets is shown in figure 2 and was discussed in detail in earlier work by the authors (Kwan & Ko 1976). The orientations or signs of the induced velocities and pressure are based on the vortex model proposed by Lau & Fisher (1975). Accordingly, the pressure fluctuations p' would be in antiphase with the axial velocity fluctuations u' at a position on the core side and in phase on the entrainment side. The pressure fluctuations would be in quadrature with the radial velocity fluctuations in both regions, with the pressure leading. Further, the axial velocity fluctuations would be in quadrature with the radial velocity fluctuations, leading the latter on the entrainment side but lagging on the core side. Finally, a non-zero value of $\overline{u'v'}$ occurs in the mixing layer where the cross-flow is significant. However, because of the existence of the two potential cores in the present case of coaxial jets, it is necessary to have a different definition for the entrainment and core side. Thus the primary mixing region and the primary potential core are regarded as situated on the core side of the secondary vortex train, while the secondary potential core and the secondary mixing region are regarded as on the entrainment side of the primary vortex train.

3. Apparatus

The experiments were carried out on jets having three different velocity ratios. The experimental rig employed in the investigation has been discussed in detail previously (Ko & Kwan 1976). The primary nozzle has a diameter of 2·04 cm, and tests were run with a primary jet efflux velocity of 60 m/s. The secondary nozzle has an outer diameter of 4 cm. With the above nozzle arrangements, the area ratio of the secondary to the primary nozzle was 2·67.

A single normal wire was used for measuring the axial component of the flow velocity. The wire had a diameter of 5×10^{-6} m and a bare length of 2 mm. The operating resistance was 15 Ω. Cross-wire probes were also used for the measurement of the axial and radial velocity fluctuations. Constant-temperature hot-wire anemometers were used with the hot-wire probes as described by Davies & Davis (1966). These anemometers were provided with both linear and nonlinear outputs.

The microphone used for the pressure measurements was a Brüel & Kjaer $\frac{1}{8}$ in. condenser microphone. The corresponding nose cone was adopted for the pressure measurements in the flow field of the jets.

A Hewlett–Packard Model 3721A correlator was used for signal correlation. The correlator provided two different modes of operation. The correlation function or covariance could be obtained either by summation or by exponential averaging. In general, the summation mode was adopted because of quicker operation. However, exponential averaging had to be employed when the correlation function was too low to be determined accurately by the summation mode.

Bradshaw, Ferriss & Johnson (1964), Ko (1974) and Ko & Davies (1975) have pointed out that the existence of a large intensity gradient makes the conventional normalized correlation coefficient entirely unsatisfactory for the proper interpretation of shear flows such as jets. The covariance, instead of the correlation coefficient, has already been adopted by Ko (1974) and Ko & Davies (1975) for single jets. It has been shown by the above workers that by considering the normalized correlation coefficient a lot of interesting and vital information was lost. Hence, for the present investigation of coaxial jets, because of the complicated jet structure consideration of the correlation coefficient would be unsatisfactory. In this respect, the covariance, which is defined as

$$C_{r\tau} = \lim_{T\to\infty} \frac{1}{T}\int_0^T u_1(r;t)\, u_2(r+\Delta r; t+\tau)\, dt,$$

was adopted.

4. Results

The present investigation was confined to the initial region of the coaxial jets, i.e. within the first eight diameters D_i of the primary jet downstream from the nozzle exit (Ko & Kwan 1976). The efflux velocity $\overline{U}_i$ of the primary jet was 60 m/s. The three different velocity ratios 0·3, 0·5 and 0·7 were investigated. The phase relationships among the different fluctuating quantities obtained from single- or two-point correlations will be presented and compared with those predicted by the model.

Single-point correlations

Covariance C_{uv} of the axial and radial velocity fluctuations. Since nonlinear outputs from the cross-wire probes and anemometers were employed in the correlations, the relative magnitudes of the correlation levels shown in the correlograms are not necessarily true. The correlation C_{uv} of the axial and radial velocity fluctuations was obtained at different axial planes of the coaxial jets. The correlograms obtained, though differing in appearance owing to different superposition effects, all illustrate clearly the same phase change as the probe was traversed across the jet plane.

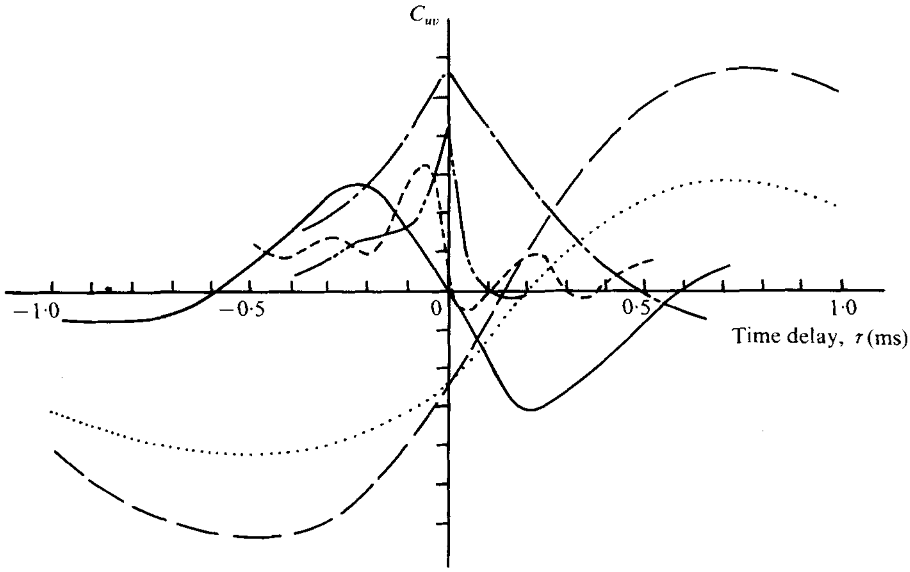

FIGURE 3. Covariance of axial and radial velocity fluctuations in a coaxial jet (arbitrary units). Velocity ratio = 0·5, $x/D_i = 2{\cdot}0$. y/D_i: ----, 0·3 (scale: 0·005); —··—, 0·6 (scale: 0·01); ——, 0·7 (scale: 0·01); —·—, 1·0 (scale: 0·1); ····, 1·5 (scale: 0·005); – – –, 1·7 (scale: 0·005).

Hence only representative results for one velocity ratio will be presented and discussed.

Figure 3 shows the correlograms obtained at the axial plane $x/D_i = 2{\cdot}0$ for a velocity ratio of 0·5. At the radial position $y/D_i = 0{\cdot}3$, i.e. within the primary potential core, a sharp peak occurs at a negative time delay and the signals are in quadrature. Inside the primary mixing region, $0{\cdot}4 \leqslant y/D_i \leqslant 0{\cdot}6$, the curves change their character entirely. The periodic nature of the correlograms disappears and the maximum positive peak suddenly shifts from a quadrature situation to an in-phase situation. This pronounced change-over of the phase relationship in the mixing region was observed by Lau *et al.* (1972) and the explanation was found in the 'extended' vortex model which they proposed. At $y/D_i = 0{\cdot}7$, the effect of the primary vortices is reduced and the observed fluctuations are mainly due to the slowly convecting secondary vortices, which are very close to the probe. This results in a complete change in the appearance of the correlogram. Instead of a sharp peak, a broad positive peak exists at a negative time delay. The signals are approximately in quadrature, with the radial velocity signal leading. This broad peak supports the finding of Ko & Kwan (1976) that the secondary vortices are mainly of low frequency while the sharp peak corresponds to the high frequency primary vortices. In the secondary mixing region, $y/D_i = 1{\cdot}0$, the axial and radial velocity fluctuation signals are again in phase. Further movement of the probe away from the mixing region and into the entrainment region, $1{\cdot}5 \leqslant y/D_i \leqslant 1{\cdot}7$, results in the signals being in another quadrature situation but with the axial velocity fluctuation signal leading.

Covariance C_{pu} of the pressure and axial velocity fluctuations. Figure 4 shows the correlograms obtained at different radial positions in the axial plane $x/D_i = 0$. These correlograms have a negative peak at small positive time delay, which means that the $-p'$ signal leads the u' signal by a small acute phase angle. At $y/D_i = 0{\cdot}3$, the correlogram has a very strange appearance: it has a sharp negative peak at approximately

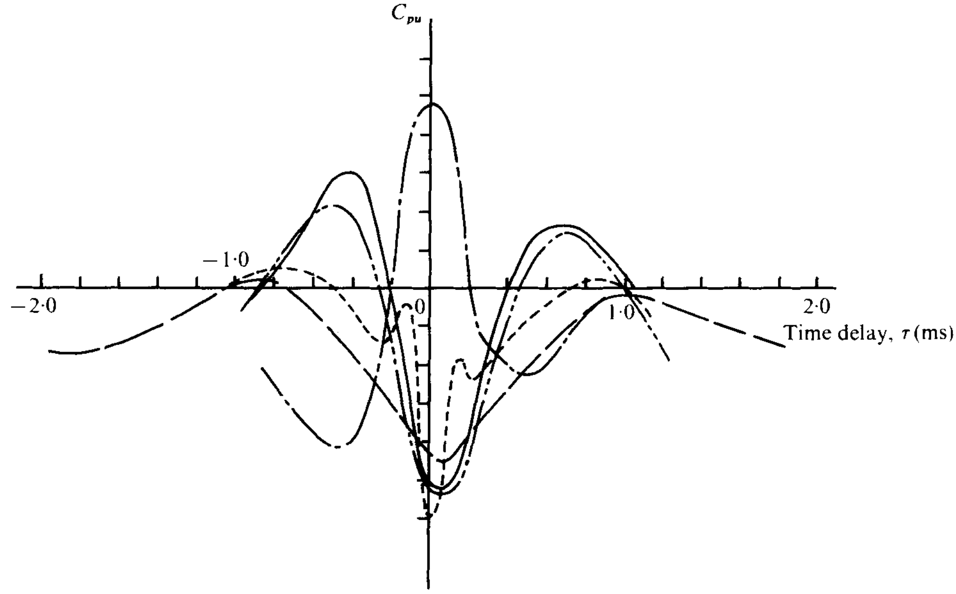

FIGURE 4. Covariance of pressure and axial velocity fluctuations for different radial positions in a coaxial jet (arbitrary units). Velocity ratio = 0·5, $x/D_i = 2·0$. y/D_i: ---, 0 (scale: 0·05); ----, 0·3 (scale: 0·1); —··—, 0·6 (scale: 0·5); ——, 0·7 (scale: 1·0); —·—, 1·1 (scale: 0·5).

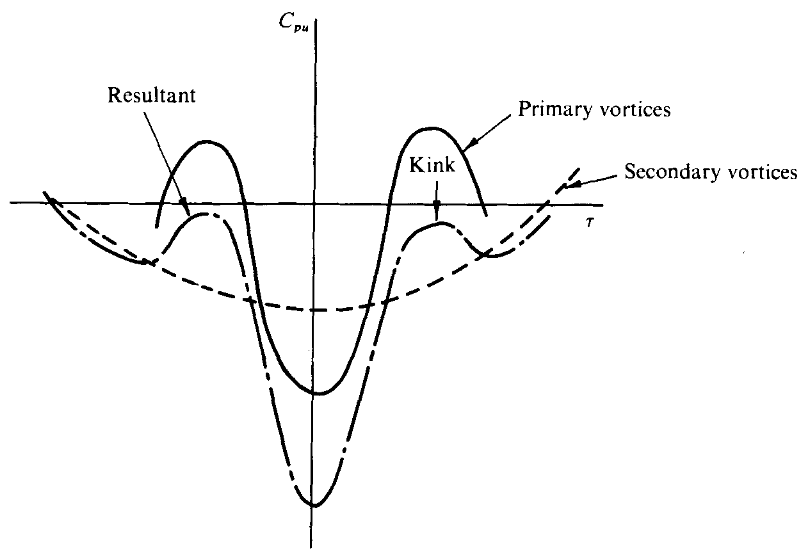

FIGURE 5. Sketch showing the superposition of the two individual correlograms.

zero time delay and two 'kinks'. These 'kinks' may be due to the superposition of the individual correlograms corresponding to the primary and secondary vortices. At this radial position the probe was on the core side of both the primary and the secondary vortices, and accordingly the correlograms corresponding to both types of vortices should have a negative peak at about zero time delay.

At larger radial distances, $0·6 \leqslant y/D_i \leqslant 0·7$, the effect of the primary vortices

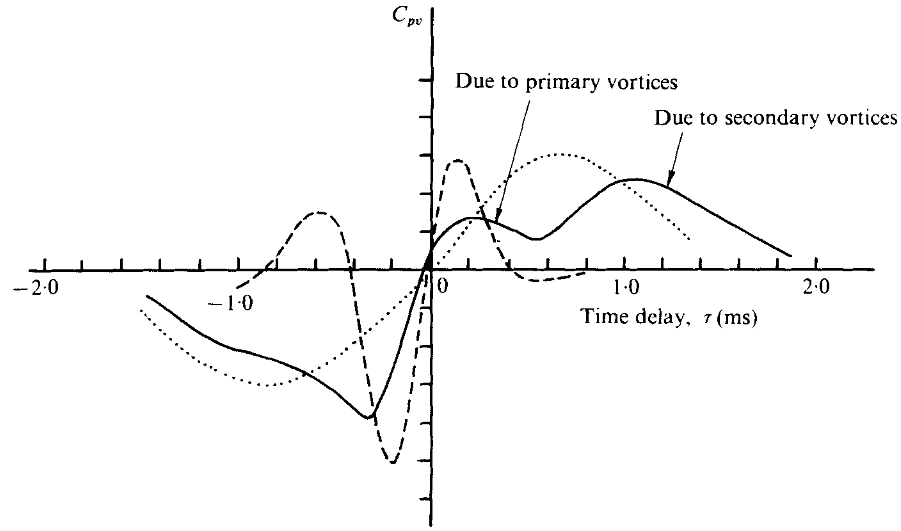

FIGURE 6. Covariance of pressure and radial velocity fluctuations in a coaxial jet (arbitrary units). Velocity ratio = 0·3, x/D_i = 2·0. y/D_i: ----, 0·3 (vertical scale: 0·02, time scale: 0·1); ——, 0·7 (vertical scale: 0·1, time scale: 0·1); ····, 1·5 (vertical scale: 0·01, time scale: 0·2).

diminishes and no kink appears in the correlogram. The measuring probe was still on the core side of the secondary mixing region and the correlation function or covariance exhibits a broad negative peak at zero time delay. On the entrainment side, $y/D_i = 1{\cdot}1$, phase inversion has occurred and the p' and u' signals are again nearly in phase.

Results obtained at different axial positions and velocity ratios, not shown here, also exhibit the same change-over from an antiphase situation on the core side to an in-phase situation on the entrainment side of either the primary or the secondary mixing region.

The reason for the 'kinks' shown in figure 4 can be very simply explained by the sketch shown in figure 5. Because of the dominant high frequency components, the correlogram due to the primary vortices can be represented by a sharp peak which covers a small time-delay interval (Ko & Davies 1971). Correspondingly, the correlogram of the low frequency secondary vortices can be represented by a broader peak which covers a bigger time-delay interval. Assuming that the interaction and cancellation of the vortices do not seriously affect the resultant correlogram, direct summation of the two individual correlograms would then give a resultant correlogram similar to the one shown in figure 4. Although this simple approach may not be able to explain fully the causes of the resultant correlograms representing the effects of both types of vortices shown in the present investigation, the simple sketch does illustrate that superposition may be the main cause.

Covariance C_{pv} of the pressure and radial velocity fluctuations. Figure 6 shows the correlation functions obtained at $x/D_i = 2{\cdot}0$ at a velocity ratio of 0·3. The pressure fluctuations p' and the radial velocity fluctuations v' retain their phase relationship irrespective of radial position. They are nearly in quadrature, with p' leading. Similar observations were also obtained for velocity ratios of 0·5 and 0·7.

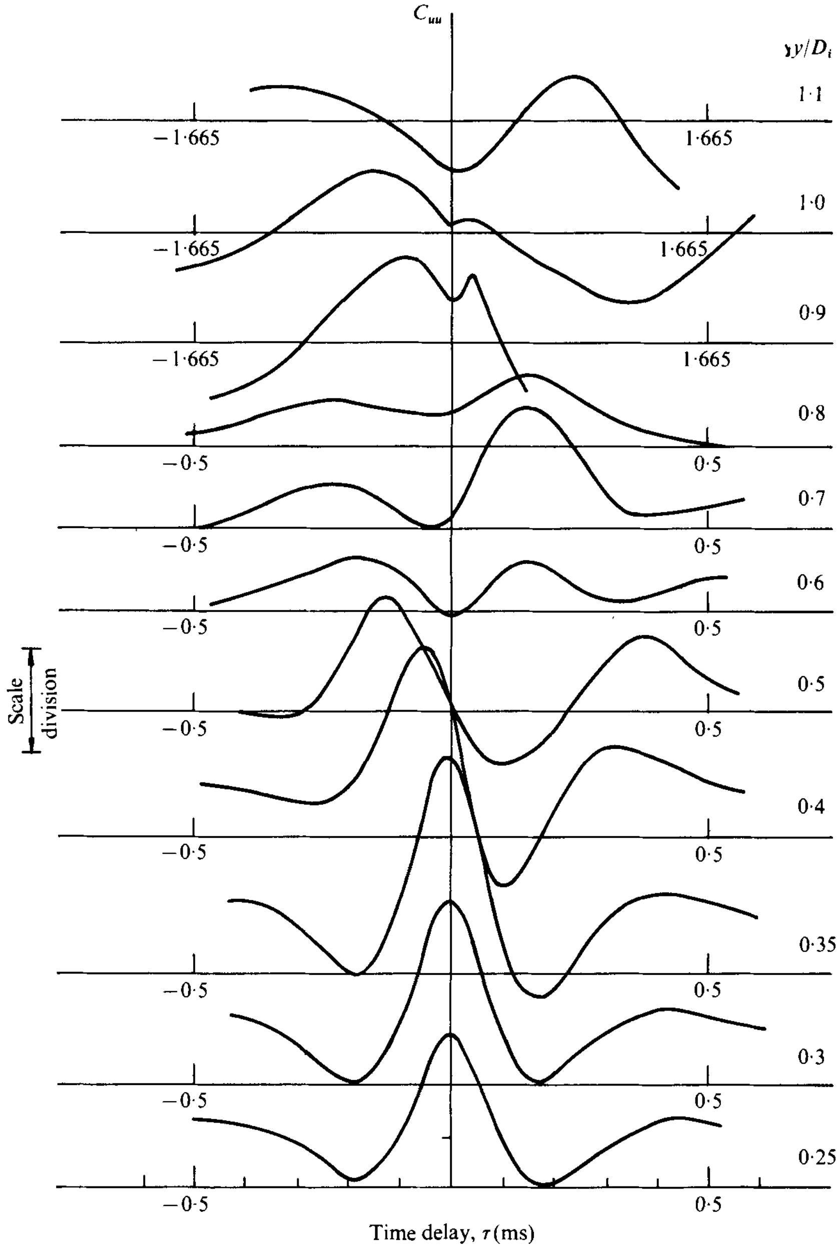

FIGURE 7. Covariance for different radial positions in a coaxial jet (arbitrary units). Velocity ratio = 0·3. Fixed wire at $x/D_i = 2{\cdot}0$, $y/D_i = 0{\cdot}15$; moving wire at $x/D_i = 2{\cdot}0$ and various y/D_i.

Radial position of moving wire, y/D_i	0·25–0·8	0·9–1·0	1·1
Scale	2×10^{-3}	1×10^{-3}	$2{\cdot}5 \times 10^{-4}$

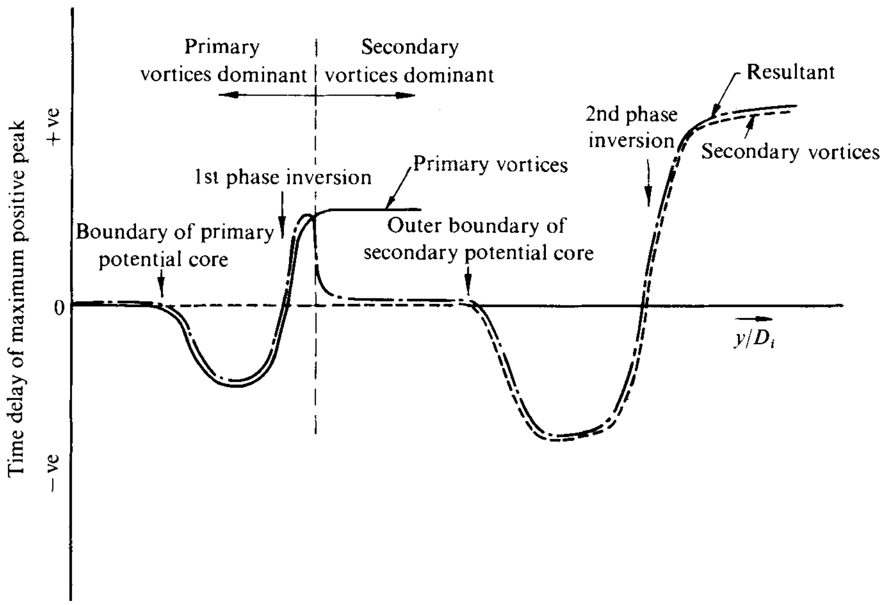

FIGURE 8. The change of phase of the u' signal with radial position.

It has also been observed that the correlograms obtained at small radial distances have extremely low covariance levels. The cancellation of the diametrically opposite vortices close to the jet axis is probably the reason for the feeble correlation obtained (Lau 1971).

Two-point correlations

Radial cross-covariance C_{uu} of the axial velocity fluctuations. The study of the variation in phase of the axial velocity fluctuations u' with radial distances across the mixing regions of the jet is important for a qualitative understanding of the vortex structure. In an investigation of a single jet Lau *et al.* (1972) observed that the u' signal underwent a phase inversion when the wire was traversed across the mixing region from the potential core to the entrainment region. Thus it is interesting to compare the results for coaxial jets with those for a single jet.

Figure 7 shows the correlograms obtained with the moving wire at different radial positions in the axial plane $x/D_i = 2{\cdot}0$. The velocity ratio was 0·3 and the fixed wire was at $x/D_i = 2{\cdot}0$, $y/D_i = 0{\cdot}15$. At this velocity ratio, the contributions from the high frequency primary vortices dominate (Ko & Kwan 1976; Kwan & Ko 1976). In the primary potential core, $y/D_i \leqslant 0{\cdot}35$, the correlogram has a positive maximum peak at zero time delay. This means that the u' signals are in phase. As the moving wire is displaced radially outwards into the primary mixing region, the maximum positive peak occurs at a negative time delay. In other words, the signal from the fixed wire lags that from the moving wire. This positive peak continues to shift to a greater negative time delay until about $y/D_i = 0{\cdot}6$. Beyond this radial positive a sudden inversion of phase occurs at $y/D_i = 0{\cdot}7$ and the maximum positive peak is found at a positive time delay.

At this velocity ratio, the contribution to the velocity fluctuations from the secondary vortices is small (Ko & Kwan 1976). Hence their contributions to the covariance

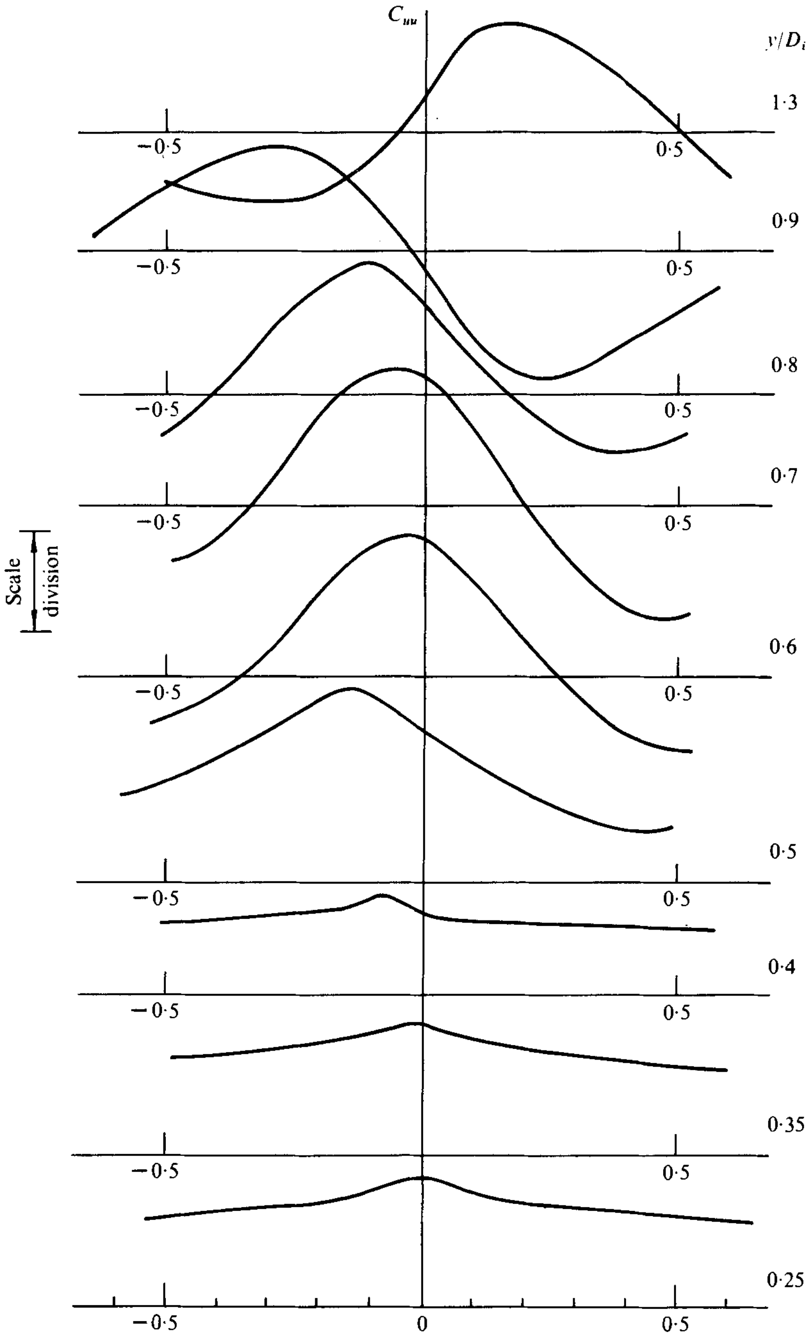

FIGURE 9. Covariance for different radial positions in a coaxial jet (arbitrary units). Velocity ratio = 0·7. Fixed wire at $x/D_i = 2{\cdot}0$, $y/D_i = 0{\cdot}15$; moving wire at $x/D_i = 2{\cdot}0$ and various y/D_i.

Radial position of moving wire, y/D_i	0·25–0·4	0·5–0·9	1·3
Scale	1×10^{-3}	5×10^{-4}	2×10^{-4}

can be revealed only after close inspection of the correlograms (figure 7). When the secondary mixing region is approached, the correlograms seem to be shifted slightly upwards, resulting in smaller negative peaks or higher minimum values in the positive covariance regime. This phenomenon was not observed by Lau *et al.* (1972). The reason for this is the presence of the weak secondary vortices and the superposition of the contributions from these weak secondary vortices and the dominant primary vortices.

At $y/D_i = 0{\cdot}7$, the correlogram has a local minimum at about zero time delay. Without the effect of the upward shift, which is due to superposition, this minimum point would have a negative value, indicating that the signals corresponding to the primary vortices were in antiphase. As the moving wire was displaced further outwards, it became closer to the secondary vortices. Even though their contributions are small, they may become more significant and dominant. This is why the correlogram at $y/D_i = 0{\cdot}9$ is very broad and is much broader than that of the primary vortices shown above. Because of this, a different scale has to be used for the time-delay axis. In addition, the curve obtained also has a very strange appearance. It has a broad peak at a negative time delay and a sharp peak at a positive time delay. This further demonstrates that the superposition of the contributions from the primary and secondary vortices is the main reason for this strange appearance.

Another phase inversion occurs as the moving wire is traversed across the secondary mixing region. The signals are approximately in antiphase when the moving wire is in the entrainment region.

The above change of phase of the signals corresponding to the two sets of vortices with radial displacement agrees fairly well with what Lau *et al.* (1972) observed for the vortices in single jets. This is more clearly illustrated in figure 8. At small radial distances, i.e. when the wire was inside the primary potential core, the correlogram is dominated by the primary vortices, which results in zero time delay of the peak. In the primary mixing region, $0{\cdot}6 \geqslant y/D_i \geqslant 0{\cdot}35$, the time delay of the maximum positive peak is negative and it attains its lowest value at about $y/D_i = 0{\cdot}6$. At about $y/D_i = 0{\cdot}7$ a sudden phase inversion occurs, resulting in a positive value of the peak time delay. For $y/D_i \geqslant 0{\cdot}8$, even though the secondary vortices are weak the proximity of the wire to these vortices renders them dominant. In this respect, the variation in the phase change described above essentially repeats itself for the secondary vortices.

Similar changes in phase relationships were obtained for a velocity ratio of 0·5. The superposition effect discussed above is more pronounced because of the stronger contributions from the secondary vortices.

For a velocity ratio of 0·7, the secondary vortices are dominant. Except when the moving wire is situated in the vicinity of the weak primary vortices, the correlograms are dominated by the secondary vortices. Figure 9 shows the correlograms obtained with the moving wire located at different radial positions in the axial plane $x/D_i = 2{\cdot}0$. The fixed wire was placed at $x/D_i = 2{\cdot}0$, $y/D_i = 0{\cdot}15$. At a small radial distance, $y/D_i = 0{\cdot}25$, the correlogram has an appearance resembling a sharp peak superimposed on a broad peak. The upward shift of the curve is the result of the superposition. This is because, even though the secondary vortices are much stronger than the primary vortices, at small radial distances the effects of the weak primary vortices will still be felt. As the moving wire enters the primary mixing region, a small bump, which is the remains of the nearly masked covariance of the primary vortices, occurs at a

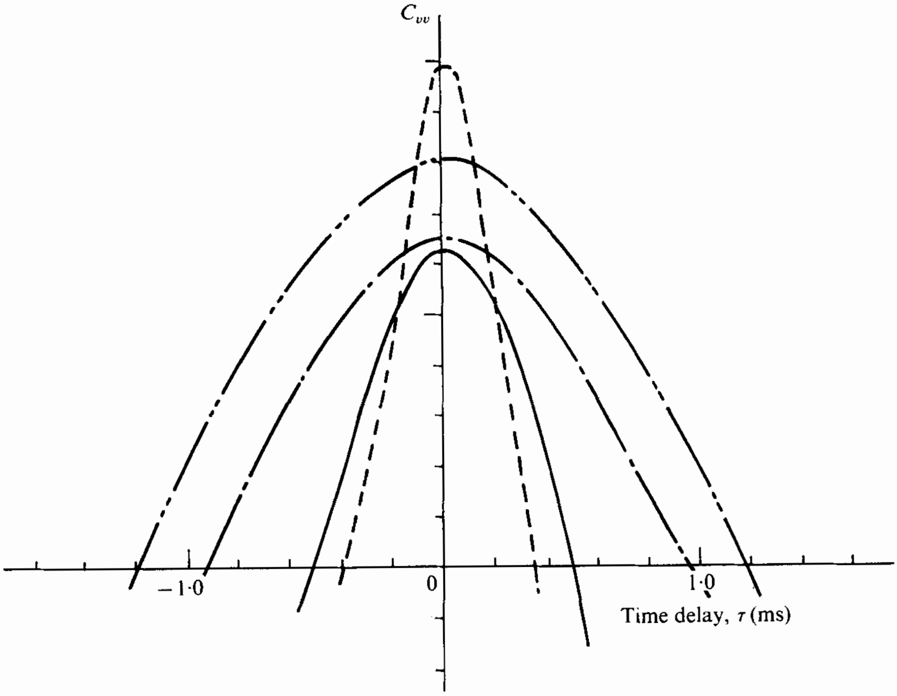

FIGURE 10. Radial cross-covariance of radial velocity fluctuations in a coaxial jet (arbitrary units). Velocity ratio $= 0{\cdot}5$. ——, fixed wire at $x/D_i = 2{\cdot}0$, $y/D_i = 0{\cdot}2$, moving wire at $x/D_i = 2{\cdot}0$, $y/D_i = 1{\cdot}6$, scale $= 0{\cdot}002$; ----, fixed wire at $x/D_i = 2{\cdot}0$, $y/D_i = 0$, moving wire at $x/D_i = 2{\cdot}0$, $y/D_i = 1{\cdot}0$, scale $= 0{\cdot}002$; —·—, fixed wire at $x/D_i = 6{\cdot}0$, $y/D_i = 0$, moving wire at $x/D_i = 6{\cdot}0$, $y/D_i = 2{\cdot}0$, scale $= 0{\cdot}002$; —··—, fixed wire at $x/D_i = 6{\cdot}0$, $y/D_i = 0{\cdot}3$, moving wire at $x/D_i = 6{\cdot}0$, $y/D_i = 2{\cdot}2$, scale $= 0{\cdot}005$.

negative time delay. This is in accordance with the earlier observations. At $y/D_i = 0{\cdot}6$, the contributions from the primary vortices are completely overwhelmed, resulting in the disappearance of the bump and the occurrence of the maximum positive peak at zero time delay. This is expected since the moving wire is still located on the core side of the secondary vortices. When the moving wire enters the secondary mixing region, phase changes similar to those for the smaller velocity ratios occur.

The change in phase of the u' signal with radial distance at larger axial distances, i.e. in the intermediate or fully merged zone, was also studied. For all velocity ratios investigated, Kwan & Ko (1976) observed decay of the non-preferred vortices in the intermediate zone. This decay of the non-preferred vortices causes the superposition effect to vanish. Thus the phase changes observed in these regions are basically similar to those Lau *et al.* (1972) obtained for single jets.

Radial cross-covariance C_{vv} of the radial velocity fluctuations. In order to study the change of phase of the v' signal with radial distance, the v' signal from the fixed wire, which was placed in the primary potential core, was correlated with the v' signal from a radially displaced wire. The correlograms thus obtained for a velocity ratio of $0{\cdot}5$ are shown in figure 10. In this figure there is no phase change of the v' signals. The correlation functions obtained for other velocity ratios, which are not shown here, also indicate that no phase change occurs in the v' signal with varying radial position.

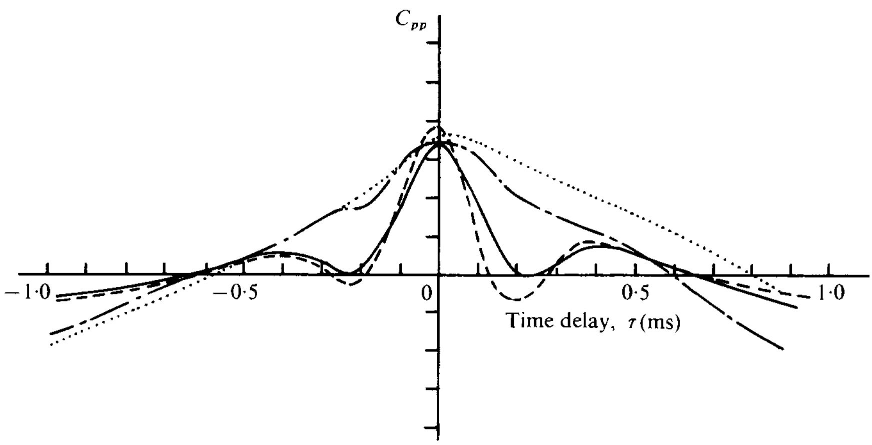

FIGURE 11. Radial cross-covariance of pressure fluctuations in a coaxial jet (arbitrary units). Velocity ratio = 0·3. Fixed wire at $x/D_i = 2{\cdot}0$, $y/D_i = 0$. Moving probe at $x/D_i = 2{\cdot}0$ and various y/D_i: ----, 0·55 (scale: 0·1); ——, 0·7 (scale: 0·1); —·—, 1·0 (scale: 0·05); ····, 1·5 (scale: 0·01).

Radial cross-covariance C_{pp} of the pressure fluctuations. Figure 11 shows the correlation results obtained at $x/D_i = 2{\cdot}0$ for a velocity ratio of 0·3. Like those for the radial velocity fluctuations, all the correlograms at different moving-wire positions possess a positive peak at approximately zero time delay and no phase change is found. Similar observations were also obtained for velocity ratios of 0·5 and 0·7.

Comparison with the model

From the correlation measurements obtained in coaxial jets, the phase relationships of the p', u' and v' signals at different locations in the jet were derived. According to the model proposed (figure 3), a sensor, when traversed across the jet plane, will pass through the trajectories of the primary and secondary vortices. The phase of the signals will undergo two phase changes, corresponding to each vortex train. According to the model, the phase changes occur when the sensor (the moving wire for the two-point correlations) is traversed across a vortex trajectory. This means that p' and v' retain their phases with the former leading by approximately 90° while u' undergoes an inversion. This behaviour is exhibited by the correlation functions obtained. The p', p' and v', v' correlation functions all have maximum positive peaks at about zero time delay irrespective of radial position; but u', u' correlation functions obtained with the fixed wire and moving wire on opposite sides of a vortex trajectory (i.e. on the entrainment and core sides of a vortex train) have a negative peak at zero time delay.

In the mixing regions, the u', v' correlation $\overline{u'v'}$ is positive. The correlation curve has a positive peak at zero time delay and loses its periodic appearance. This indicates that a different mechanism, the flow induced by the basic vortex, is responsible for the existence of the Reynolds stress. This mechanism has the overall effect of producing a positive u' signal when v' is positive and a negative u' whenever v' is negative. Therefore a positive value of $\overline{u'v'}$ is generated.

5. Conclusions

The single-point correlation measurements conducted in the initial region of coaxial jets give the following phase relationships between the pressure fluctuations and the axial and radial velocity fluctuations.

On the core side of the vortices,

$-p'$ leads u' by a small angle,

p' leads v' by approximately 90°

and v' leads u' by an angle slightly less than 90°.

On the entrainment side of the vortices,

p' and u' are approximately in phase,

p' leads v' by approximately 90°

and v' lags u' by an angle slightly greater than 90°.

In the mixing region,

u' and v' are in phase.

The two-point correlations of p', u' and v' signals show that p' and v' do not undergo any phase change during a traverse from the core side of a mixing region to the entrainment side. The signal that undergoes inversion is the u' signal.

All the above phase relationships obtained in coaxial jets basically agree with the experimental results for single jets. This indicates that the coherent structures in coaxial jets and in single jets are physically similar. This means that the arrays of toroidal vortices in the mixing regions of coaxial jets are similar to those in single jets.

The work was supported in part by a research grant from the University of Hong Kong.

REFERENCES

BRADSHAW, P., FERRISS, D. H. & JOHNSON, R. F. 1964 Turbulence in the noise-producing region of a circular jet. *J. Fluid Mech.* **19**, 591–624.

CHAN, Y. Y. 1974 Spatial wave in turbulent jets. *Phys. Fluids* **17**, 46–53.

CROW, S. C. & CHAMPAGNE, F. H. 1971 Orderly structure in jet turbulence. *J. Fluid Mech.* **48**, 547–591.

DAVIES, P. O. A. L. & DAVIS, M. R. 1966 Hot-wire anemometer. *I.S.A.V. Rep.* no. 155.

KO, N. W. M. 1974 On the correlation technique in the subsonic jet. *Noise, Shock, Vibration Conf. Monash Univ., Melbourne*, pp. 226–235.

KO, N. W. M. & DAVIES, P. O. A. L. 1971 The near field within the potential core of subsonic cold jets. *J. Fluid Mech.* **50**, 49–78.

KO, N. W. M. & DAVIES, P. O. A. L. 1975 Some covariance measurements in a subsonic cold jet. *J. Sound Vib.* **41**, 347–358.

KO, N. W. M. & KWAN, A. S. H. 1974 Experimental investigation of subsonic coaxial jets. *5th Australasian Conf. Hydraul. Fluid Mech.* pp. 609–616.

KO, N. W. M. & KWAN, A. S. H. 1976 The initial region of subsonic coaxial jets. *J. Fluid Mech.* **73**, 305–332.

KWAN, A. S. H. & KO, N. W. M. 1976 Coherent structures in subsonic coaxial jets. *J. Sound Vib.* **48**, 203–219.

LAU, J. C. 1971 The coherent structure of jets. Ph.D. thesis, University of Southampton.

LAU, J. C. & FISHER, M. J. 1975 The vortex-street structure of 'turbulent' jets. Part 1. *J. Fluid Mech.* **67**, 299–337.

LAU, J. C., FISHER, M. J. & FUCHS, H. V. 1972 The intrinsic structure of turbulent jets. *J. Sound Vib.* **22**, 379–406.

LAUFER, J., KAPLAN, R. E. & CHU, W. T. 1974 On the generation of jet noise. *AGARD Conf. Proc.* no. 131, paper 21.

MICHALKE, A. & FUCHS, H. V. 1975 On turbulence and noise of an axisymmetric shear flow. *J. Fluid Mech.* **70**, 179–205.

WINANT, C. D. & BROWAND, F. K. 1974 Vortex pairing: the mechanism of turbulent mixing layer growth at moderate Reynolds number. *J. Fluid Mech.* **63**, 237–255.