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The distortion of a jet by tabs

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In an attempt to explain the discrepancies that have been observed in the spread of nominally axisymmetric jets, an experimental investigation has been carried out in which the effects of a number of factors which it was thought might be important to jet development have been studied. These factors included the nozzle boundary-layer thickness, turbulence level and convergence. However, over the limited range of the tests, it was found that none of these factors had a very strong influence on the jet development. By contrast, the insertion of small rectangular tabs into the jet flow on the nozzle perimeter was found to have a very profound effect on the jet development. In particular, it was found that just two tabs produced gross distortions in the jet development resulting in the jet almost splitting in two with high velocity regions on either side of the diameter joining the tabs. Some explanations for this effect based on further tests with wedges are put forward.

In addition to the measurements of the mean flow field, a few spectrum and correlation measurements are reported for jets both from a clean nozzle and also from a nozzle with two tabs. In the former tests, evidence additional to the results of other experimenters was found for the existence of flow structures which have some coherence around the entire circumference of the jet. It has been suggested that these 'vortex rings' or 'puffs' may be of some importance in producing jet noise and it seems that the effect of inserting tabs is to prevent the occurrence of these structures.

1. Introduction

In carrying out model tests to study various aspects of the aerodynamics of VTOL aircraft in the hovering phase of flight, it has been noted that there are significant differences in the decay of the centre-line velocity in the various axisymmetric jets used in the experiments. These differences are important because they imply that the jets were spreading at different rates and that the entrainment into them was different. Good examples of these differences can be seen in figure 2, which shows the decay of the jet centre-line velocity from experiments of Kuhn (1959), Gentry & Margarson (1966) and Bradbury (1972). Although the jet nozzle details in each of these tests differed from one another, there was nothing in the experimental arrangements which would have led one to believe that the differences in the jet development would be as marked as they appear to be. It is obviously important to try to establish the cause of these differences, and this paper contains the results of experiments to study a variety of factors which it was thought might be responsible for the variations in the development of axisymmetric jets. In addition to the application to VTOL aircraft aerodynamics, some results of the present work might also be of relevance to work on jet noise.

In § 2, the jet rig used in the experiments is described. Section 3 contains the results of the experiments. The first factors to be studied were the jet nozzle boundary-layer thickness, jet nozzle turbulence level and nozzle convergence. However, none of these factors had a very significant effect on the jet development and only the briefest details of the results are given. Tests in which small rectangular tabs were inserted into the jet on the nozzle perimeter are then described. It is found that these produced large changes in the jet development as indicated by the decay of the centre-line mean velocity. The effect is more pronounced in a jet with only two tabs than it is in one with, say, four or eight tabs. Further results seem to show that this change in development is brought about by the circumferential variations in the flow angle produced by the tabs. These flow-angle changes produce gross distortions in the jet cross-section as it spreads downstream and it is shown from direct measurements with a pulsed-wire anemometer that this distortion is accompanied by increased entrainment into the jet. Next, § 4 contains a few comments on the occurrence of vortex-ring structures in axisymmetric jets.

It should perhaps be noted at the outset that the results contained in this paper may not always be as comprehensive as one would wish. However, some of the results are possibly rather surprising and, on this basis, may be of some interest.

2. Details of the axisymmetric jet apparatus

In order to be able to control carefully the jet nozzle conditions, the jet development was studied on a much larger scale than is usual. The jet rig is shown in figure 1. It consisted of a jet nozzle 8 in. in diameter supplied from a 5 h.p. centrifugal fan via a 2 ft square settling chamber and a smooth contraction. The section of parallel nozzle between the end of the contraction and the nozzle exit was 15 in. long. As can be seen from figure 1, the jet issued from a ground board 8 × 8 ft and the entire jet rig was mounted on a 6 ft high platform.

The mean velocity across the nozzle exit was found to be uniform to within 2 % except in the boundary-layer region near the nozzle walls. The turbulence level in the plane of the jet nozzle was about 0·5 %.

All the mean velocity measurements in the jet were made with a Pitot-static tube 0·05 in. in diameter. The high turbulence levels and the wide range of flow directions encountered in the present tests caused, of course, substantial errors in the velocities deduced from the Pitot-static tube readings, but these do not have any significant effect on the interpretation of some of the gross effects on jet development observed in the present tests.

A five-hole pitch-and-yaw tube was used to determine the flow direction in the immediate neighbourhood of the nozzle and, finally, a pulsed-wire anemometer was used outside the jet to measure entrainment velocities directly.

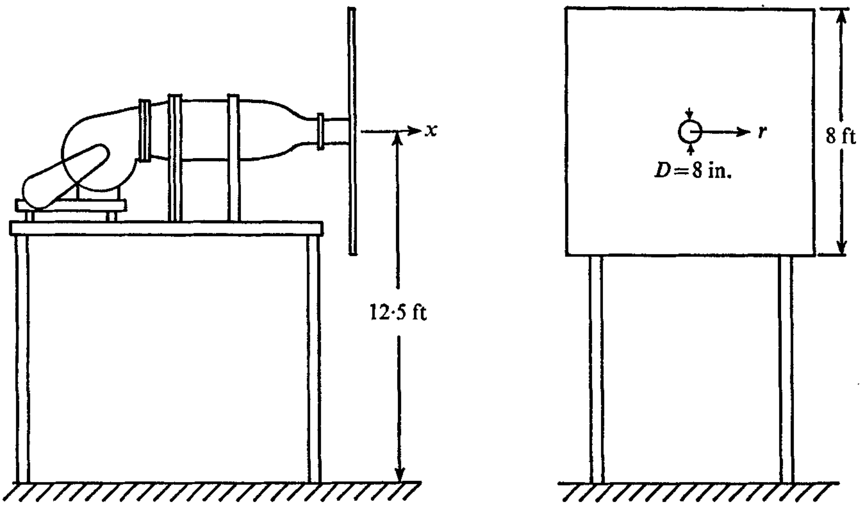

FIGURE 1. The jet apparatus.

3. Results of experiments on the jet development

3.1. *Tests on the effects of nozzle boundary-layer thickness, nozzle turbulence level and nozzle convergence on the jet development.*

Figure 2 contains results for the decay of the jet centre-line velocity from the present nozzle at a Reynolds number of 6×10^5 compared with some earlier results obtained by the present author on a quite different jet rig in which the nozzle diameter was only 1 in. at a Reynolds number of $0{\cdot}5 \times 10^5$. These results are in very good agreement with one another and demonstrate the presence of a potential core of length about 6 jet nozzle diameters and a subsequent jet velocity decay like x^{-1}. They also confirm the expected absence of any direct Reynolds number effect on the jet development.

The first factors studied in the present tests were the jet nozzle boundary-layer thickness, jet nozzle turbulence level and nozzle convergence. None of these factors had any very significant effect on the jet development and the results will be only very briefly discussed.

As far as boundary-layer thickness is concerned, it was found that the jet centre-line velocity was not observably affected by the turbulent nozzle boundary-layer thickness when the displacement thickness was less than 0·01 of the jet diameter. However, in a single test in which the nozzle boundary-layer displacement thickness was about 0·01 times the nozzle diameter, the potential core region was shortened by about half a diameter. The boundary layer in this case was probably not fully turbulent and it may be that this had some effect on the initial development of the shear layers. However, compared with the gross effects being sought, the effect of the boundary-layer thickness is clearly not of great significance.

A few tests were carried out in which a coarse turbulence grid was mounted at the beginning of the parallel section of the nozzle. This increased the turbulence

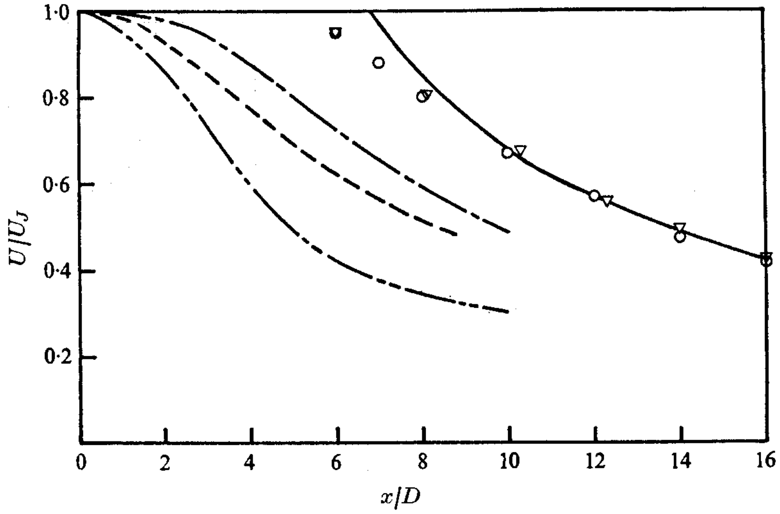

FIGURE 2. The decay of the jet centre-line velocity from various experiments. ○, present tests, $Re = 6 \times 10^{-5}$; ▽, Bradbury (1972), $Re = 0{\cdot}5 \times 10^{5}$; – – –, Kuhn (1959); —·—, —··—, Gentry & Margarson (1966); ——, $6{\cdot}8(x/D)^{-1}$, see Bradbury (1972).

level at the nozzle exit to 5·6 % with a longitudinal integral scale of 0·75 in. This produced no observable effect on the jet centre-line velocity variation. This is not altogether surprising as it might be argued that jet nozzle turbulence is unlikely to have much influence until it reaches an intensity comparable to that occurring naturally in the mixing layers at the edge of the potential core. This implies that jet nozzle turbulence is unlikely to have much effect until it reaches an intensity of about 20 %.

Some tests were also carried out in which wooden rings 1 in. thick were mounted in the nozzle at the nozzle exit. These rings were tapered to produce uniform nozzle convergence at the exit of 10° or 45°. However, the decay of the jet centre-line velocity and the variation of the turbulence intensity along the jet centre-line were almost unaffected by the presence of the convergent rings. Figure 3 shows the results for the decay of the centre-line velocity. These are included simply to be contrasted with the results in the next subsection, in which circumferential variations in the flow angle seemed to produce very large effects on the jet development.

It should perhaps also be mentioned that, in all the tests mentioned in this section, check measurements of both the mean velocity and turbulent intensity were made to ensure that the flow development was always axisymmetric. It should also be noted that the results for the centre-line variation of the mean velocity and turbulent intensity (figure 5 below) from the clean nozzle in the present tests are in good agreement with the results of, for example, Bradshaw, Ferriss & Johnson (1964) and Crow & Champagne (1971).

3.2. *Tests on the effects of tabs on the jet development*

Before the tests to be described in this section were carried out, the presence of vortex-ring structures in the potential core region had already been observed in

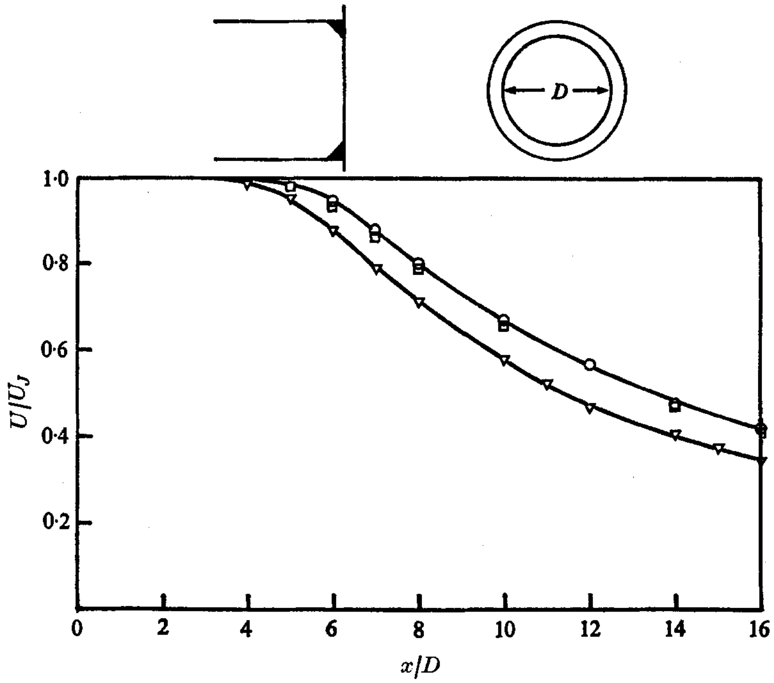

FIGURE 3. The effect of nozzle convergence on the decay of the jet centre-line velocity. ○, clean jet; □, 10° ring; ▽, 45° ring.

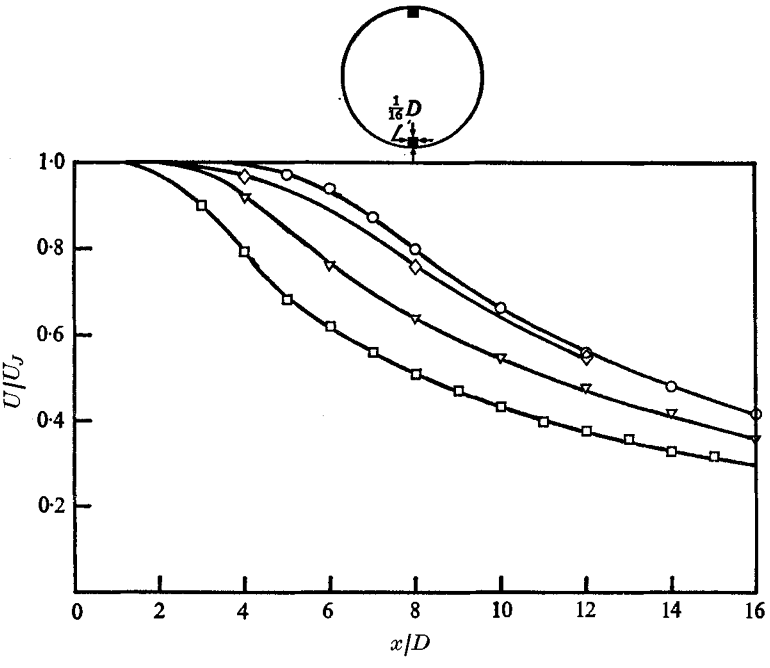

FIGURE 4. The effect of tabs on the decay of the jet centre-line velocity. ○, no tabs; ◇, 8 tabs; ▽, 4 tabs; □, 2 tabs.

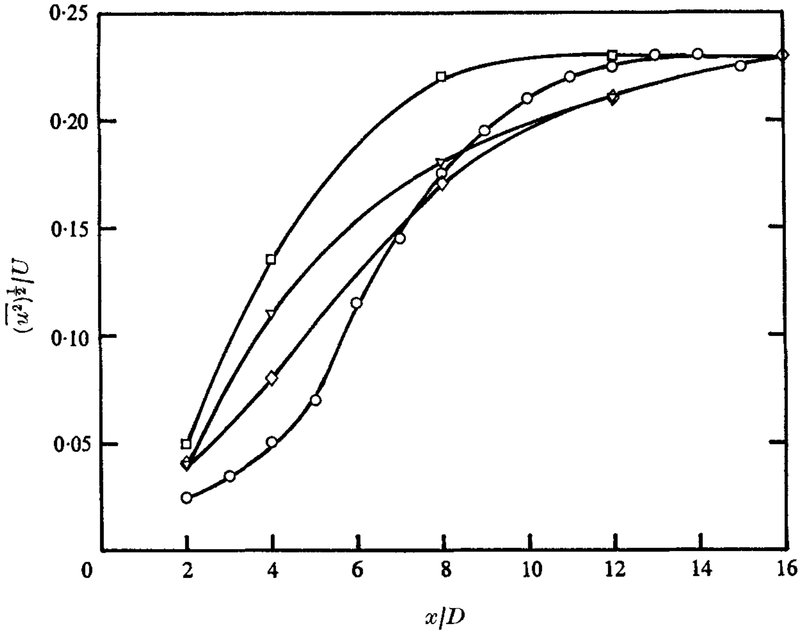

FIGURE 5. The effect of tabs on the jet centre-line turbulent intensity. Symbols as in figure 4.

general accordance with the observations of some other experimenters. The results of some measurements on these ring structures will be described in §4. However, these rings are known to cause a variety of problems in open jet tunnels and, in order to suppress them, numerous small tabs are usually mounted around the perimeter of the open jet nozzle. Initially it was thought that the vortex rings might play an important part in the initial development of the jet so some tests were carried out in which various numbers of tabs of various sizes were mounted on the jet nozzle perimeter. These results are too numerous to include here but figure 4 shows a typical set of results which illustrates a most interesting effect. In the tests shown in figure 4, the tabs were square with sides of $\frac{1}{16}$ of the jet diameter. When eight tabs were mounted around the perimeter of the nozzle, the effect on the jet development was not very large. However, when the number of tabs was reduced to two, the apparent potential-core length was reduced to about two diameters followed by a rapid decay of the centre-line mean velocity. The centre-line turbulent intensities relative to the local mean velocity were also increased as is shown by the results in figure 5.

From some traverses at two and four diameters downstream of the jet nozzle with two tabs mounted in it, the velocity contours shown in figure 6 were constructed. Detailed traverses were made in only one quadrant of the jet although check measurements showed a high degree of symmetry in the other quadrants. These results show how the tabs tend to split the jet almost in two with high velocity cores on either side of the tabs.

There seemed to be two possible mechanisms by which gross distortions on this scale could occur, namely (i) by the 'stirring' action of trailing vortex motions

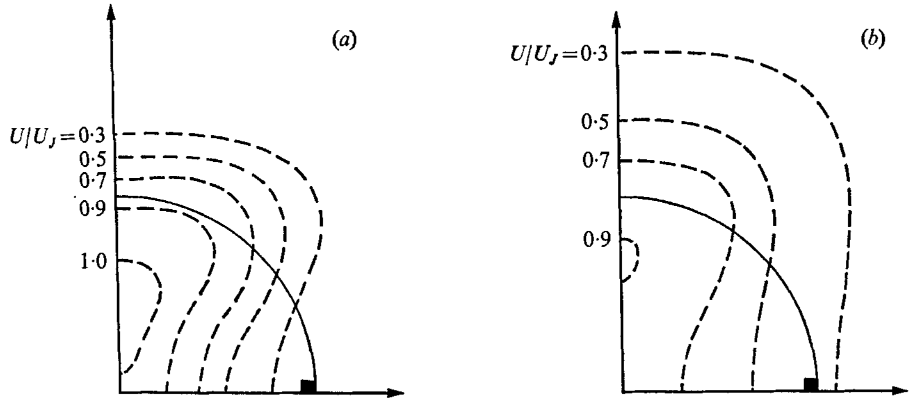

FIGURE 6. Velocity contours downstream of a jet with two tabs. (a) $x/D = 2$. (b) $x/D = 4$.

shed from the tabs and (ii) by the simple deflexion of the flow over the tabs such as might occur in a potential flow jet with circumferential variations in flow angle. In order to check for the presence of vortex motions, it would strictly have been necessary to make circulation measurements in the flow behind the tabs but, in view of the magnitude of the distortions, it seemed likely that the presence of vortex motions would have been easily observable with a simple wool tuft. However, no such motions could be detected and so it seemed more probable that the distortion arose from the circumferential variations in flow angle produced by the tabs. Some evidence for the possibility that variations in flow angle might be responsible for the distortion of the jet can be found in a paper by Taylor (1960) on the formation of thin flat sheets of water. It would appear that, in water jets, angular variations around the circumference of a jet do not die away downstream but can lead to gross changes in the cross-sectional shape of the jet. In fact, on reflexion, it is difficult to construct any simple physical argument which would lead to a mechanism involving potential-flow pressure changes for reducing circumferential flow-angle variations in the case of a flow with free surfaces.

Obviously, with air-into-air jets, the turbulent mixing greatly complicates the flow structure and ultimately the jet structure returns to the axisymmetric self-preserving type† which has been the subject of so many investigations. Nevertheless, in the region near the jet nozzle, it seems very likely that flow-angle variations can lead to gross distortions in the jet development.

3.3. *Tests on the effect of wedges on the jet development*

In addition to the tab tests, some tests were carried out in which two wedges were mounted opposite each other on the nozzle walls. The end cross-section of the wedges was the same as that of the tabs. The effect of these wedges on the centre-line velocity variation of the jet is shown in figure 7. It is clear that increasing the wedge angle has a progressive effect and it would seem that wedges with an angle of less than 5° have very little effect on the development of the jet.

† Tests in the fully turbulent region beyond about fifteen diameters downstream showed that an axisymmetric jet structure had already re-established itself.

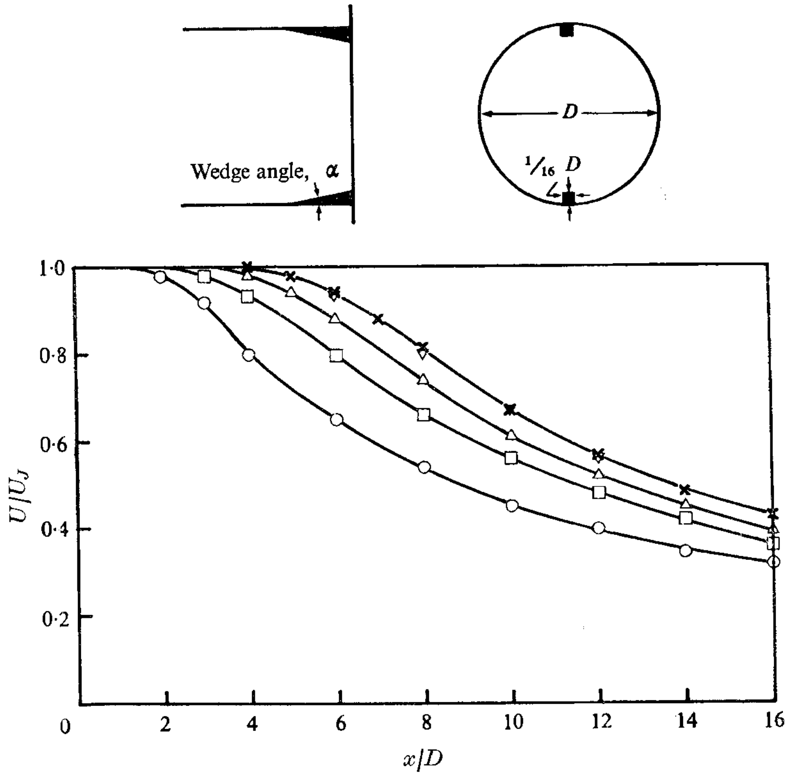

FIGURE 7. The effect of wedge angle on the decay of the jet centre-line velocity. ×, clean jet; ▽, $\alpha = 5^\circ$; △, $\alpha = 20^\circ$; □, $\alpha = 45^\circ$; ○, $\alpha = 90^\circ$.

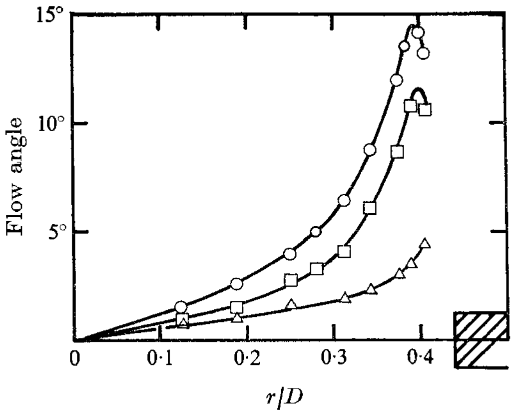

FIGURE 8. The effect of wedge angle on the flow-angle variation across the jet nozzle exit. Symbols as if figure 7.

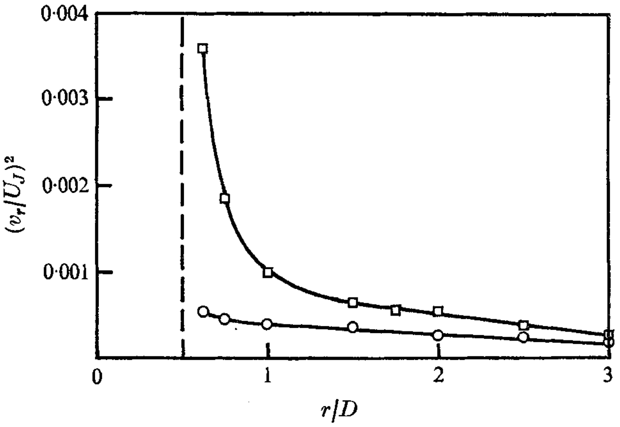

FIGURE 9. The effect of tabs on the entrainment into the jet. □, 2 tabs; ○, no tabs.

Figure 8 shows the flow-angle variation at the nozzle exit along the diameter joining the two tabs. These results show that the wedges and tabs produce flow-angle variations across the entire jet nozzle and that the angles are progressively increased by increasing the wedge angle. It should also be mentioned that several checks were made to ensure that the flow angle on the diameter at right angles to that joining the tabs was always zero in the tests with wedges and tabs.

3.4. *Entrainment into the jet*

Although the effect of the tabs is to produce a gross distortion of the jet cross-section, it seemed advisable to check directly that this resulted in increased entrainment into the jet. Thus figure 9 shows mean entrainment velocities measured with a pulsed-wire anemometer at a distance of 0·25 of a jet diameter from the ground board. Although this was a rather arbitrary and isolated test, it does demonstrate the increased entrainment that accompanies the insertion of the two tabs into the jet.

4. Vortex rings

From an examination of numerous experimental investigations of the initial region of 'clean' axisymmetric jets, it is clear that there are structures which have some coherence over the entire cross-section of the jets. Crow & Champagne (1971) refer to these as 'puffs' but we shall loosely refer to them as 'vortex rings'. At first sight, it is tempting to try to characterize the frequency n of these vortex rings by a single Strouhal number nd/U_J, where d is the nozzle diameter and U_J is the jet nozzle velocity. However, if we consider the development of the mixing layers, which we might expect to develop rather like plane mixing layers at least for the first two diameters downstream from the nozzle, then it is necessary if these layers are to have a self-preserving type of structure for the Strouhal number nx/U_J to remain constant. This latter condition would require the frequency of the vortex rings to vary with distance downstream from the nozzle and this could only be achieved by allowing the vortex rings to coalesce in some way. There are now numerous flow-visualization films† demonstrating that this sort of thing can occur and it will result, of course, in a broadening of the spectrum of the velocity fluctuations associated with the motion of the vortex rings. Under these circumstances, the simple notion of a well-defined Strouhal number becomes ambiguous irrespective of the length scale used in its definition.

From the work of Bradshaw *et al.* (1964) and Lau (1971), peaks in the spectra of the turbulence in the mixing layers can be observed and it seems likely that these were associated with vortex-ring structures. The frequency of the peaks in their spectral curves are more nearly consistent with a constant value of nx/U_J but this is only very approximate and the effects both of axisymmetry and of the time taken to establish self-preservation in a plane mixing layer combine no doubt to ensure that simple notions about vortex-ring structures will not find unambiguous support from experimental data.

In the present experiments, a few measurements of spectra were made on the centre-line of the jet. Unfortunately, owing to limitations on time, these are less comprehensive than one would wish but they do add something to our general store of information about the flow in the initial region of a jet. Figure 10 shows a complete u-component spectrum on the centre-line of the jet at $x/D = 4$. A few spectrum measurements in the region of the peak frequency for $x/D = 2$ are also shown. The measurements were made with a standard B & K $\frac{1}{3}$ octave spectrum analyser with a filter range from 2 Hz to 20 kHz. The results show a peak in the spectra although clearly the structures associated with the peak are not anything like as well defined as the very narrow band vortex shedding that occurs, say, downstream of a circular cylinder. The results in figure 10 seem to exhibit a peak at a nearly constant Strouhal number nd/U_J of about 0·45, which agrees closely with the observations of Lau (1971). This near constancy of the Strouhal number nd/U_J on the flow centre-line seems to contradict the observations of Bradshaw *et al.* (1964) and Lau (1971) in the mixing regions. However, velocity fluctuations in the region of the peak frequency on the flow centre-line are essentially potential-flow fluctuations and they arise from the integrated contributions from the vortex rings along the length of the potential core. Since, owing to coalescence, these increase in strength as the distance from the nozzle increases, it is quite feasible that the centre-line peaks may be at some average frequency of the occurrence of vortex rings in the mixing layers with a weighting in frequency towards the end of the potential core. It is interesting to note that Crow & Champagne (1971) obtained a Strouhal number nd/U_J of about 0·3 on the basis of the frequency of smoke 'puffs' in some flow-visualization studies. It seems likely that the 'puffs' counted in such observations would be the largest coherent structures which could be observed before they were absorbed into the fully turbulent flow downstream of the potential core. Thus, one might expect this Strouhal number to be even more closely associated with the occurrecne of the ring structures at the end of the potential core and this might account for

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† Several beautiful examples of coalescing vortex structures were shown at the conference at the University of Southampton in March 1974 entitled "Coherent Structures in Turbulence" (see Davies & Yule 1975).

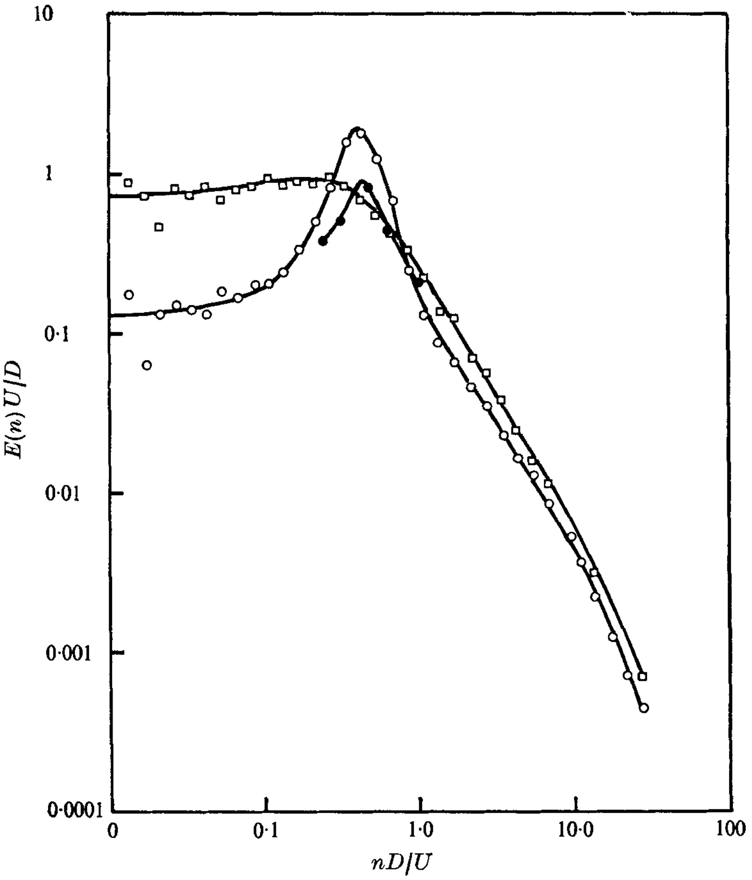

FIGURE 10. The effect of tabs on the turbulence spectrum on the jet centre-line. ○, no tabs, $x/D = 4$; ●, no tabs, $x/D = 2$; □, 2 tabs, $x/D = 4$.

the somewhat lower value of the Strouhal number obtained from such observations compared with the present centre-line spectrum measurements.

The final measurements to be reported on the flow from a clean jet nozzle are some spatial correlation measurements at $x/D = 2$. Two hot-wire anemometers were mounted in the flow at a fixed radius from the jet centre-line and the correlation between them was measured as one wire was traversed circumferentially away from the other, fixed wire. Two tests were carried out, at radii of $r/D = 0{\cdot}25$ and $r/D = 0{\cdot}5$. Thus, in the former the wires were in a mainly potential flow region, whereas in the latter they were near the centre of the fully turbulent mixing layers. The results of these measurements are shown in figure 11. Those at $r/D = 0{\cdot}25$ clearly demonstrate the presence of a structure which is coherent around the entire circumference of the jet but, since it contains only a small proportion of the total turbulent energy, the extent of the correlation in the mixing layers at $r/D = 0{\cdot}5$ is fixed mainly by the scale of the general turbulent motion, which is much less than that of the ring structures.

The presence of highly coherent structures in the initial region of a jet has been of some interest to those concerned with jet noise, both theoretically and

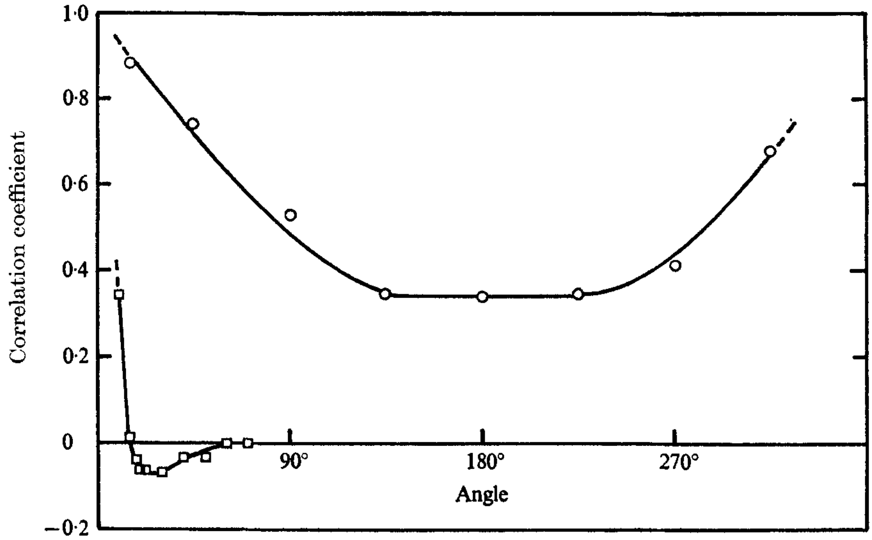

FIGURE 11. Circumferential correlations in a jet without tabs. ○, $r/D = 0{\cdot}25$; □, $r/D = 0{\cdot}5$. ($x/D = 2$.)

experimentally, and the only remaining observation from the present tests is that the vortex-ring structures can apparently be suppressed by the insertion of small tabs. Figure 10 shows a u-component spectrum on the jet centre-line at $x/D = 4$ from a jet with two tabs. Although the lower frequency content of the spectrum is increased, the peak in the spectrum is entirely eliminated. Since the jet development is so profoundly affected by only two tabs, it is possible that the sound produced by such a jet might be very different from that produced by a jet from a clean nozzle.

5. Conclusions

The original aim of the present work was to try and find possible explanations for the discrepancies between various investigations of nominally axisymmetric jet development. It has been demonstrated that circumferential variations in flow angle are certainly capable of producing gross distortions in the jet development and this is a most likely cause of the discrepancies. Some tests, not reported here, have in fact been carried out on a model similar to the one used by Gentry & Margarson (1966) and it was found that there were large variations in flow angle of the sort which do lead to a distorted jet development.

Although the practical aim of the present work was directed towards the aerodynamics of VTOL aircraft, it may also have some small relevance to the problem of jet noise. Although a tremendous amount of work has been done on a variety of silencing arrangements including the use of tabs, nevertheless, so far as the authors are aware, there do not appear to have been many studies of the actual development of the jet behind these silencing devices. Thus, the present results may be of some interest as they demonstrate the gross effects that can be easily produced by comparatively small circumferential variations in flow angle.

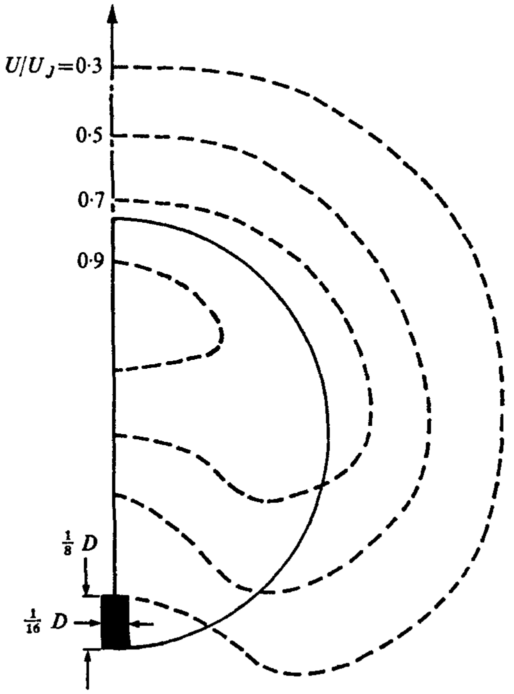

FIGURE 12. Velocity contours downstream of a jet with one tab. $x/D = 4$.

It is also perhaps worth noting that even one tab is capable of producing dramatic changes in the jet development and, as a final illustration of the effect, figure 12 shows constant velocity contours in a jet with one tab at $x/D = 4$.

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