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FLYING HOT WIRE STUDIES OF VORTEX MOTIONS IN COFLOWING JETS & WAKES

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SUMMARY An experimental method which, when used in conjunction with flow visualization, allows instantaneous velocity vector fields to be rapidly measured and related to the smoke patterns is outlined. The basis of the method is a flying hot-wire system. The system was used to study the vortex patterns which occur in coflowing jets and wakes at moderate Reynolds numbers (of order 500) which were made perfectly periodic in time by artificial stimulation. The experiments were completely deterministic and no averaging of data was necessary.

1. INTRODUCTION

Attempts at studying three-dimensional eddying motions have usually been hampered by randomness in the flow and washout of data. Perry and Lim (1978) have however, avoided these problems by studying forced periodic coflowing jets and wakes at Reynolds numbers of the order 1000. By laterally perturbing a glass tube from which smoke was issuing, they were able able to 'freeze' the naturally occurring eddying motions. The term 'freeze' is used to indicate perfect periodicity in time. The structures would thus appear 'frozen' when viewed under stroboscopic light of the appropriate frequency.

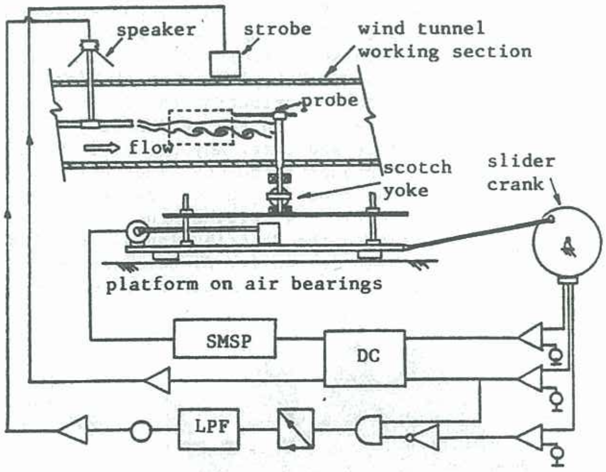
It has been the aim of many people (e.g. see Davies and Yule (1975) and Falco (1977)) to measure entire instantaneous velocity vector fields surrounding eddying motions and to relate these fields with the smoke patterns. Perry, Lim and Chong (1980, referred to as Perry et al.) were able to do this to two of the wake-type structures of Perry and Lim, using a sampling technique based on the phase of the tube oscillation. However, the technique they employed was fairly limiting in that it required the use of Taylor's hypothesis. It was therefore unsuitable for the jet-type structures, which grow and change their shape with streamwise distance, or for flow situations where vortex pairing was occurring. On the whole, their method was fairly time consuming and experiments were often unsuccessful due to the structures changing their shape with time and the hot-wire calibrations drifting in the time that was required to perform the experiment.

One aim of the present investigation was to develop an experimental technique to allow entire velocity vector fields about eddying motions to be measured in a streamwise plane of symmetry and to relate them to flow visualisation results. The technique had to achieve this without the use of Taylor's hypothesis and involve the minimum of assumptions. It also had to do this within a six minute period, since the structures remained stable only for about six minutes before changes in the density of the smoke altered them. Also, the wire calibrations altered noticeably after about ten minutes of use in the smoke environment. Another aim was to further study the coherent structures of Perry and Lim.

2. APPARATUS AND METHODS

Since Taylor's hypothesis was not to be used and time was a limiting factor, a set of moving hot-wires were used. The hot-wire probe was oscillated back and forth along the working section of the tunnel and data was sampled on the upstream stroke. This allowed the rapid sampling of the flow along the streamwise direction and also had the advantage of an imposed bias velocity. The imposed bias velocity reduces the 'cone-angle' of the velocity vector relative to the crossed-wires, enabling the calibrations to be curve-fitted with a Taylor series expansion consisting of a small number of terms. All flows studied were externally stimulated and the data was sampled on the basis of the phase of the stimulation signal. Photographs of the flows were also taken on the basis of the phase of the stimulation signal.

The experimental setup consisted of a wind tunnel with a glass tube, from which the structures issued, along the tunnel streamwise centreline. The tunnel was that used by Perry and Lim. With reference to figure 1, instantaneous velocities were sampled by a set of crossed-wires mounted on a sting which passed through a slot along the floor of the working section. The sting was mounted on a scotch yoke mechanism. This, in turn, was mounted on a platform which sat on an air bearing sled. The sled was oscillated horizontally by a variable stroke slider-crank mechanism. The platform could also be traversed vertically by means of a stepping motor connected to four vertical screws.



SMSP - stepping motor signal processor
LPF - low pass filter
DC - digital computer

FIGURE 1 Schematic diagram of overall experimental setup including signal processing system. Hot-wire sample grid is shown as a dashed rectangle.

The wires were dynamically calibrated in situ (far from the wake of the tube). Vertical calibrations were done with the scotch yoke and horizontal calibrations were done with the slider-crank. The calibration technique was similar to that used by Perry and Watmuff (1981). Due to the extremely low velocities encountered (typically 0 to 1 m/s), the method of calibration was modified such that it did not require the use of a pitot-static tube. This involved the so called 'bootstrapping' method. Third order polynomial curve-fits were also used for the calibrations (i.e. for the velocity versus voltage curves), and the first and higher order terms were evaluated from the sensitivities determined by the dynamic calibration. Details of the calibration method can be found in Perry (1982) and in Tan (1983).

The experiment consisted of sampling data on one horizontal level, for eight strokes of the slider-crank, moving to the next level and sampling again, and so on, until the desired number of levels were sampled. It produced the vector fields of 32 phases within a six minute period (each cycle of oscillation was divided into 32 phases). No averaging of data was done.

Data was sampled on-line by a digital computer which was triggered by pulses produced by a slotted disc attached to the shaft of the slider-crank. Since the sled was attached to the slider-crank, each of these pulses also corresponded to a horizontal displacement. The position of the wire was therefore known for every sample taken. The pulses were also processed and used to oscillate the glass tube. The tube oscillation, wire displacement and sampling were therefore coupled together. The method as described would give the same phase at the same position on each stroke. However, all 32 phases of the hot-wire signal are required at each sample position. This was achieved by introducing a phase jump into the tube oscillation signal at the end of each stroke in conjunction with an interpolation scheme.

Although no averaging of data was carried out, the vector fields produced were very clear and revealed the flow features adequately. A method of smoothing the data 'across the phases' was devised however, to allow the vorticity distributions to be computed without too much scatter. For each sample level, a three-dimensional plot of the velocity component magnitude (s) versus phase (ϕ) and position (x) can be produced (see figure 2). As can be seen, there are fairly orderly rows of peaks and troughs at some angle to the ϕ and x axes. This angle will give the 'convection' or 'phase' velocity of the structures. If the distribution of s were plotted at the 'convection velocity angle', the distribution should be a straight line or curve, depending on the periodicity of the structures in space and time. Any noise however, would be observed as a higher frequency fluctuation on the line or curve. The smoothing procedure was based on finding the convection velocity of the structures and doing a curve-fit to the distribution along lines at the convection velocity angle. By selecting the order of the curve-fit series, noise can be smoothed out.

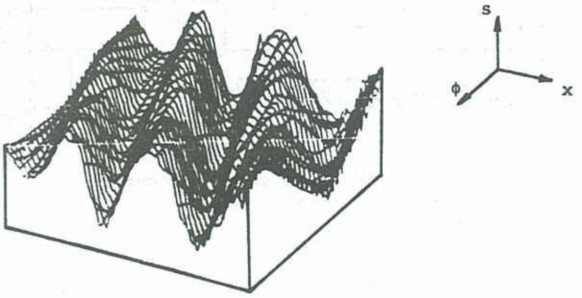


FIGURE 2 Three-dimensional magnitude/phase/position plot of experimental results (typical level)

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Vector fields

One of the structures measured by Perry et al. was the negatively buoyant wake (the classification used for defining jets and wakes is that suggested by Perry and Lim). The vector field was obtained, allowing comparisons to be made with those obtained by Perry et al. The direction field is shown in figure 3 (direction fields are vector fields where only the directions of the vectors are shown). The direction field has been plotted as seen by an observer with a negative vertical convection velocity as well as the horizontal convection velocity given by the smoothing process.

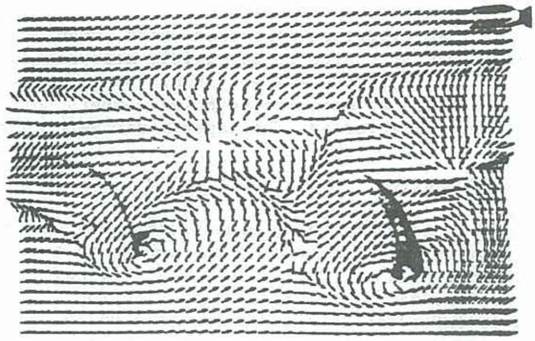


FIGURE 3 Direction field of a negatively buoyant wake superimposed on its smoke photograph (smoke is shown in negative for clarity)

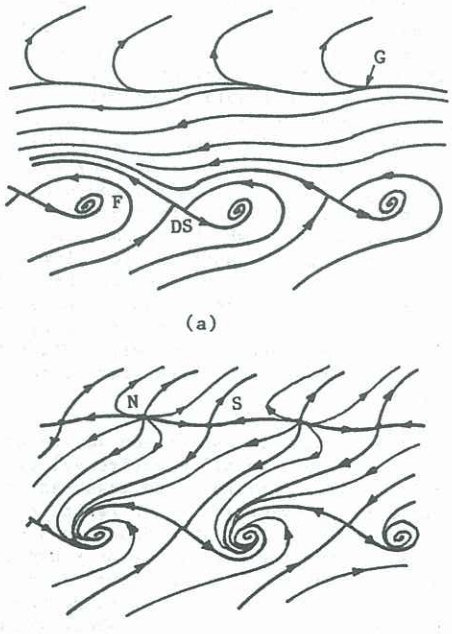
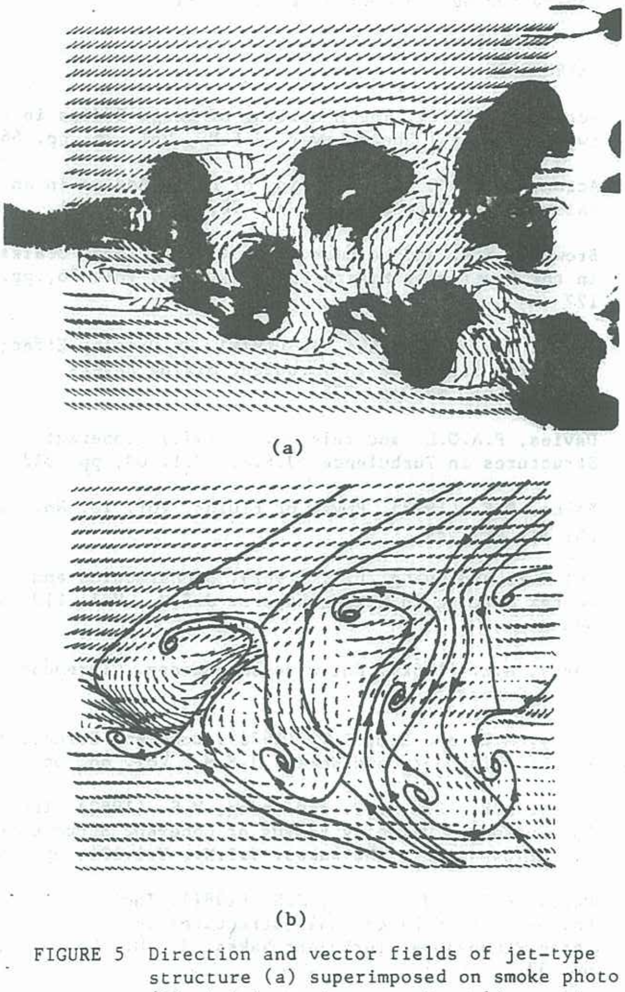


FIGURE 4 Deduced instantaneous streamline patterns (a) from Perry et al. (b) authors'
G - singular streamline
F - focus
N - node
S - saddle
DS - dislocated saddle

Figures 4 show the deduced instantaneous streamline patterns of Perry et al. and of the authors'. The results are similar except that the singular streamline (labelled G) in their results has been replaced by a series of interconnected nodes and saddles in the authors'. The difference can be explained by an incorrect selection of convection velocity by Perry et al. since a 10% increase in the convection velocity of viewing the authors' results also produces a singular streamline.

The vector and direction fields of a jet-type structure is shown in figures 5. It is a fairly complicated jet structure which bifurcates. The features of the structure can be seen clearly, although the vectors do not 'line-up' as well with the smoke as in the case of the wake. This is mainly due to the difficulty encountered in the selection of an appropriate vertical convection velocity.



(a)

(b)

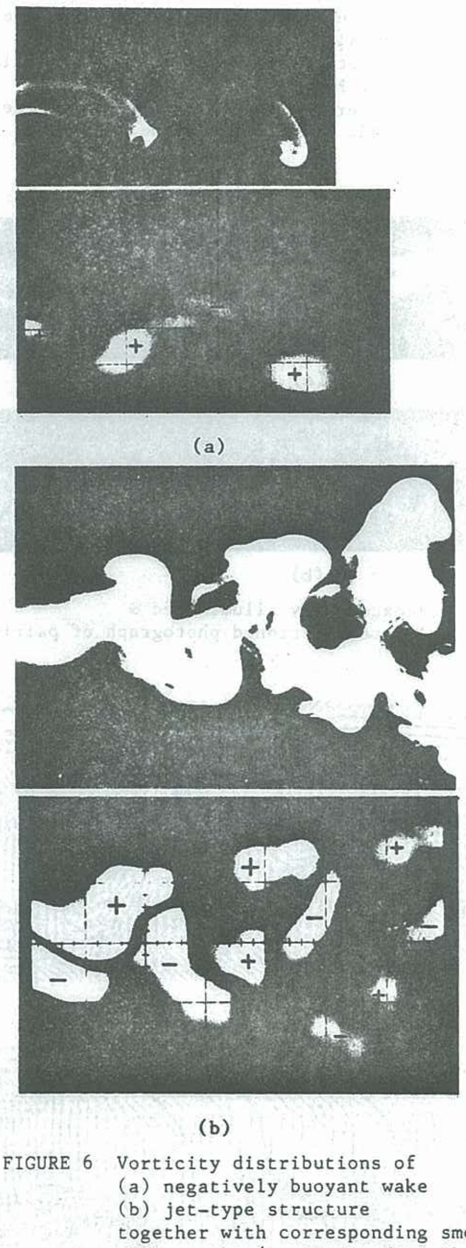
FIGURE 5 Direction and vector fields of jet-type structure (a) superimposed on smoke photo (b) with instantaneous streamline pattern

The jets do not change their horizontal spacing much but the vertical spacing does change, due to spreading and/or bifurcation. The vector field of the wake was done with a vertical convection velocity. Selection of a vertical convection velocity for a jet is more difficult since different parts of it do not convect at the same rate. Since the jets are double-sided, the vector fields were done in two halves; the upper half with a positive vertical convection velocity and the lower half with a negative (worked out from the spreading angle of the structures as given by the smoke photographs). The horizontal convection velocity is the same for both halves. One is therefore following the eddies on the upper and lower halves. Figure 5(b) shows the vector field of the jet with the separatrices of the conjectured streamline pattern superimposed.

3.2 Vorticity Distributions

The vorticity distributions of the various flow cases were also computed and plotted on a dual beam storage scope. The intensity of the scope was used to represent the magnitude of the vorticity at each point. Brighter points represent higher absolute values of vorticity. In this way, it was hoped that a plot which resembled the smoke photographs would be produced.

Figure 6 shows the vorticity distribution of the structures measured. There is some similarity to the smoke photographs. The concentrations of vorticity correspond to the foci in the flow.



(a)

(b)

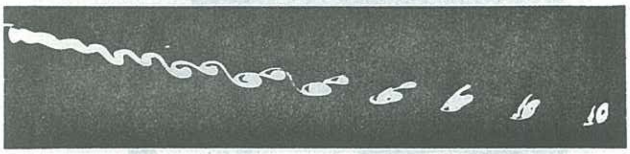
FIGURE 6 Vorticity distributions of
(a) negatively buoyant wake
(b) jet-type structure
together with corresponding smoke photographs (vorticity distributions and smoke photographs are printed to the same scale)

3.3 Vortex pairing

The interest in vortex pairing arose with investigations into organised structures in turbulent shear flow. Studies have been made of pairing in shear layers and in axisymmetric jets. The work shows that it plays an important role in the behaviour of the flows studied (i.e. in their growth, entrainment, production of Reynolds stress, noise production, etc.... See Brown and Roshko (1974), Browand and Weidman (1976), Zaman and Hussain (1980), Acton (1976, 1980) for example). The investigations, so far, have been limited to basically two-dimensional flows. Since a great number of flows of interest and practical importance are three-dimensional, the question naturally arises as to whether vortex pairing plays a role in their development and behaviour, or indeed, whether it occurs at all. Since the Perry and Lim type structures provided a source of 'well-behaved' three-dimensional eddies, it was decided to attempt to induce them to pair.

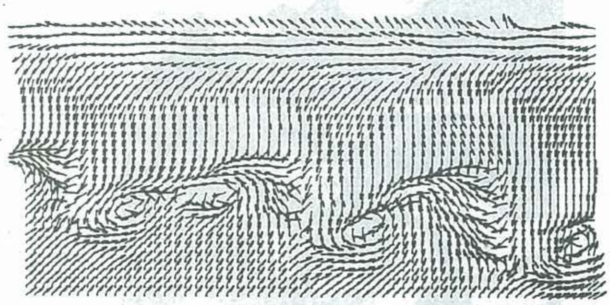
The technique of Ho and Huang (1982) was used. They had induced pairing and 'collective interaction' (i.e. coalescing of any number of eddies) of two-dimensional structures in a plane mixing layer by exciting the flow at a fundamental frequency and various subharmonics. A negatively buoyant wake was stimulated at two frequencies. Figures 7 show externally illuminated and laser-sectioned photographs of the structures produced. They appear to be pairing or merging.

(a)

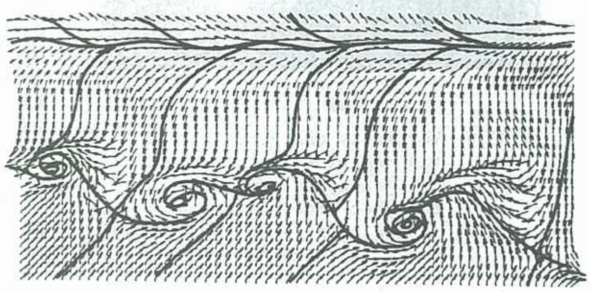


(b)

FIGURE 7 (a) externally illuminated & (b) laser-sectioned photograph of pairing



(a)



(b)

FIGURE 8 Direction fields of (a) phase 1 & (b) phase 10 showing pairing process. Conjectured instantaneous streamline pattern is superimposed on (b)

The experimental apparatus was used to obtain the vector fields of the flow and figures 8 show the direction fields of two phases during the pairing event. The conjectured streamline pattern is shown superimposed on figure 8(b). As can be seen, the front eddy of each 'pair' begins to rotate around the rear eddy and then appears to merge into it.

4. CONCLUSION

The experimental setup described has proved to be useful in studying flows around structures which can be made perfectly periodic in time. Vector fields of multiple phases can be taken within a six minute period, allowing animations of the flow-field to be made.

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REFERENCES

Acton, E. (1976). The Modelling of Large Eddies in a two-dimensional Shear Layer. J.F.M., Vol. 76, pp. 561

Acton, E. (1980). A Modelling of Large Eddies in an Axisymmetric Jet. J.F.M., Vol. 98, pt. 1, pp. 1

Browand, F.K. and Weidman, P.D. (1976). Large Scales in the Developing Mixing Layer. J.F.M., Vol. 76, pp. 127

Brown, G.L. and Roshko, A. (1974). On Density Effects and Large Structure in Turbulent Mixing Layers. J.F.M., Vol. 64, pp. 775

Davies, P.A.O.L. and Yule, A.J. (1975). Coherent Structures in Turbulence. J.F.M., Vol. 69, pp. 513

Falco, R.E. (1977). Phys. of Fluids, Vol. 20, No. 10, pt. II, pp. 124

Ho, C.M. and Huang, L.S. (1982). Subharmonics and Vortex Merging in Mixing Layers. J.F.M., Vol. 119, pp. 443

Perry, A.E. (1982). Hot-wire anemometry. Clarendon Press Oxford.

Perry, A.E. and Lim, T.T. (1978). Coherent Structures in Coflowing Jets and Wakes. J.F.M., Vol. 88, pp. 451

Perry, A.E., Lim, T.T. and Chong, M.S. (1980). The Instantaneous Velocity Fields of Coherent Structures in Coflowing Jets and Wakes. J.F.M., Vol.101, pp. 243

Perry, A.E. and Watmuff, J.H. (1981). The Phase-Averaged Large-Scale Structures in Three-Dimensional Turbulent Wakes. J.F.M., Vol. 103, pp. 33

Tan, D.K.M. (1983). Simple three-dimensional Vortex Motions in Jets, Wakes and Boundary Layers. Ph.D thesis, Univ. of Melbourne, Melbourne.

Zaman, K.B.M.Q. and Hussain, A.K.M.F. (1980) I & II. Vortex Pairing in a Circular Jet under controlled excitation. J.F.M., Vol. 101, pp. 449