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Coherent structures in coflowing jets and wakes

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By applying small lateral oscillations to a glass tube from which smoke was issuing, perfectly periodic coflowing jets and wake structures were produced at Reynolds numbers of order 300–1000. These structures remained coherent over long streamwise distances and appeared to be perfectly frozen when viewed under stroboscopic light which was synchronized with the disturbing oscillation. By the use of strobing laser beams, longitudinal sections of the structures were photographed and an account of the geometry of these structures is reported.

When the tube was unforced, similar structures occurred but they modulated in scale and frequency, and their orientation was random.

A classification of structures is presented and examples are demonstrated in naturally occurring situations such as smoke from a cigarette, the wake behind a three-dimensional blunt body, and the high Reynolds number flow in a plume from a chimney. It is suggested that an examination of these structures may give some insight into the large-scale motion in fully turbulent flow.

1. Introduction

The idea of producing coherent structures using external disturbances has existed for many years. Le Conte (1858) observed the jumping of a naked fish-tail flame in response to audible beats during a musical party in the United States. Tyndall (1867) pointed out that the flame is not essential; the same effect could occur in any jet of fluid under suitable conditions. Close observations of jets of smoke showed that acoustic excitation would cause the cylindrical vortex layer to roll up into periodic 'spirals'. This phenomenon was also studied extensively by Rayleigh (1884, 1945).

Periodic spirals are also observed to occur in coflowing jets and wakes without artificial excitation, but are difficult to examine because of their unsteadiness. These structures are either the result of a growth from small natural external disturbances near the source or the result of large self-sustained oscillations in the flow at the source (e.g. wakes resembling Kármán vortex streets). By the use of artificial periodic disturbances, much of the randomness can be removed, making the structures more amenable to study. Such structures have a high coherence and are best observed at moderately low Reynolds numbers (of order 300–1000). Here 'coherent' means that a recognizable smoke pattern persists in the streamwise direction although it may change its shape slightly and its length and velocity scales may be undergoing continual variation in the streamwise direction.

Besides being of great intrinsic interest, it is shown here that these structures might have relevance to the large-scale motions in high Reynolds number fully turbulent flow. So little is known or understood about eddying motion in general, particularly in three-dimensions, that it seems that any new information would be welcome. Townsend (1976) devotes much of his book to speculating on the geometry of eddies. So also does Turner (1973), when considering buoyant plumes and billowing clouds. A study of flow structures which are coherent and also periodic in time for all positions in space appears to be a logical step towards an understanding of the more complex random flow situations.

Over recent years, great interest has been revived in studying coherent flow structures produced by external stimulation, in particular by Becker & Massaro (1968) and Crow & Champagne (1971). Comprehensive reports on coherent structures of a more general nature have been made by Laufer (1975), Davies & Yule (1975) and Roshko (1976). The motivation behind this revival of interest is that if the structures are also periodic in time they can be conditionally sampled on the basis of phase using modern computing techniques. This, it is hoped, will lead to a detailed understanding of eddying motion. Generally the structures so far produced are not very periodic, and 'washout' of the data occurs, causing lack of resolution of the structural details. This is due to the high Reynolds numbers used. Particularly periodic and coherent structures have been produced behind vibrating and non-vibrating cylinders in cross-flow at Reynolds numbers of order 1000. See Koopmann (1967), Zdravkovich (1969) and Griffiin & Ramberg (1974). To the authors' knowledge, a similar degree of coherence and periodicity has not been observed in three dimensions. Periodic coherent structures of a three-dimensional nature are of more interest since these have the properties of vortex stretching as they develop and grow in the streamwise direction. This is an important ingredient in the modelling of turbulent motions.

The authors therefore decided to investigate methods of external stimulation which would produce flows which are coherent and also periodic in time for all positions in space in nominally axisymmetric jets and wakes at Reynolds numbers of the order of 300–1000. Perfect periodicity occurs when smoke patterns appear to be frozen when viewed under stroboscopic light which is synchronized with the external disturbances. Only then is it possible to examine in detail the intricate and highly convoluted geometry of these flow structures. The structures may appear to be synthetic, but it is demonstrated that in the 'natural' or unforced situation similar structures occur. The forcing is used to 'lock in' the structures so that they can be examined in detail.

The authors believe that a fruitful way of studying the geometry of these structures is to use the critical-point theory developed by Lighthill (1963), Oswatitsch (1958), Perry & Fairlie (1974), Smith (1972), Hunt (1977, private communication) and more recently by Cantwell, Coles & Dimotakis (1977). This theory could be used to study the geometry of instantaneous streamlines and could give insight into how the external irrotational fluid is assimilated into coflowing jets and wakes. In the experiments reported here, the authors have confined themselves to a preliminary study of the geometry of smoke patterns. Smoke forms a family of streak lines rather than a family of instantaneous streamlines and hence is rather difficult to interpret in unsteady flow. However, it does give an indication of the geometry of vortex sheets since the outer surface of the initial cylinder of smoke is a vortex sheet. The authors hope to study the instantaneous velocity field at a later date.

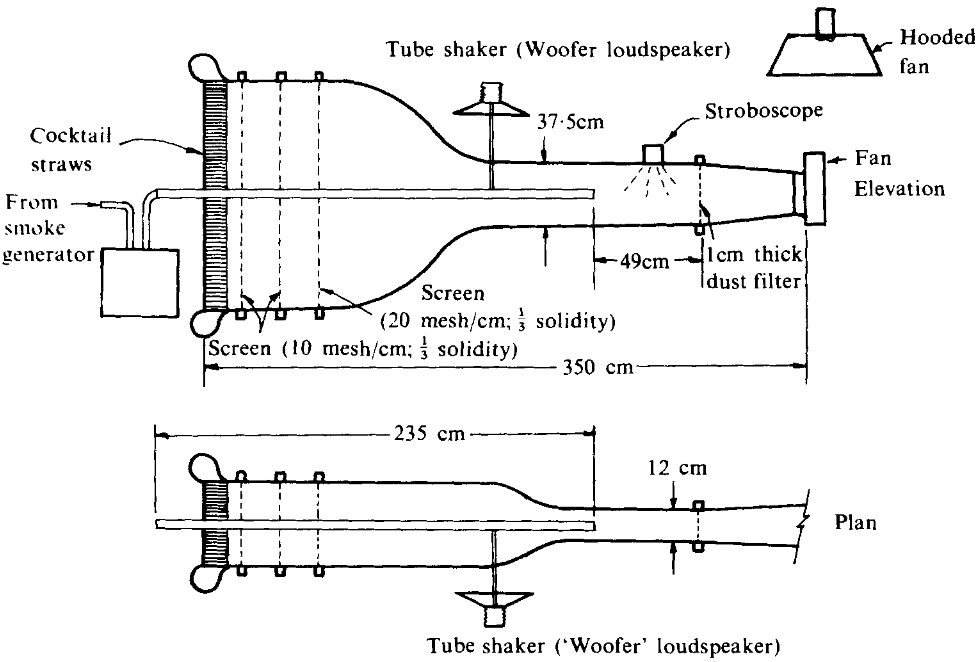

FIGURE 1. Layout of wind tunnel.

2. Apparatus and procedure

Experiments were initially performed with a tube which expelled smoke into the laboratory. Axial velocity perturbations were induced in the tube flow by pumping air into and out of a chamber with a speaker upstream of the tube outlet. The flow was illuminated by stroboscopic light which was synchronized with the stimulation. It was found that only the first two wavelengths of structure had any apparent coherence. On the other hand, when the tube exit was oscillated laterally by very small amplitude vibrations using an electro-mechanical device, very long spectacular structures could be produced with as many as 30–40 wavelengths of coherence. The structures did tend to wander with room turbulence and so a special wind tunnel was built to shield the flow. Figure 1 shows this.† An added advantage of this arrangement is that an external flow can be adjusted to produce coflowing jets or wakes. A whole range of structures can be produced by adjusting the external flow and the compressed-air supply to the smoke tube. The amplitude and frequency of oscillation also influence the shape of the structures, particularly when the amplitude is sufficiently large. By running the stroboscope slightly unsynchronized with the vibration, a 'slow motion' sequence of images is formed which enables one to study the streamwise development of a given structure. This aids greatly in understanding the geometry of the flow.

In general the amplitude of oscillation was increased slowly from zero to a point where the structures just became frozen and this produced patterns corresponding closely to those observed in the unforced situation. Since the resemblance is so close,

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† A slightly less satisfactory method for locking in the structures is to use a speaker mounted over a hole in the tunnel floor just below the tube outlet. With this method wakes were difficult to lock in.

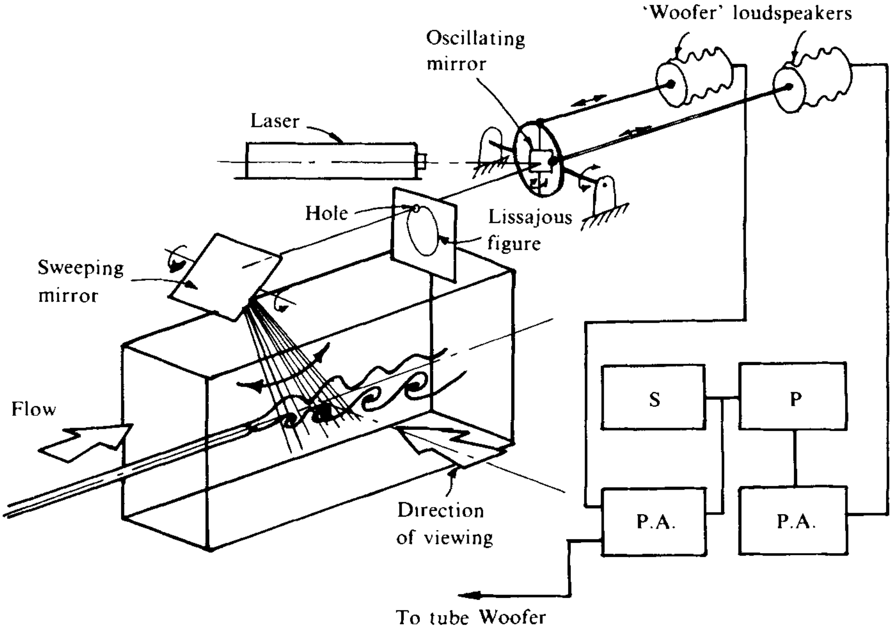


FIGURE 2. Laser strobing apparatus. S, sine wave generator; P, phase shifting network; P.A., power amplifier.

the authors conjecture that the dynamics of the motion produced by a vibrating glass tube do not differ significantly from the dynamics in structures which are produced from a 'naturally' oscillating stream tube some distance from the outlet.

A glass tube of inner diameter 1·3 cm and outer diameter 1·5 cm was used. The amplitude of vibration was a fraction of a millimetre. The flow from the tube could be varied from 0 to 2 m/s and the external flow was typically 0·4 m/s. The Reynolds number based on the tube diameter and relative velocities was typically of the order of 1000. The frequency of oscillation was varied from 8 to 50 Hz. The major dimensions of the tunnel are indicated in figure 1. The tube was partly supported by the honeycomb and three screens. Two aerofoil-shaped links were glued solidly to the tube upstream of the working section. These links were rigidly connected to speakers so that the tube could be oscillated vertically or horizontally. Unless stated otherwise the tube was oscillated vertically in all tests reported here.

Smoke was generated by a C. F. Taylor smoke generator using Shell Ondina 17 grade oil. Rather than expelling the smoke directly from the tunnel to the outside of the building, a hooded fan was used as shown in the figure. This arrangement was found to be necessary in order to isolate the working section from fluctuations in back pressure from outside.

To obtain detailed information regarding the geometry of the structures, longitudinal section photographs were taken on Polaroid 3000 ASA film using a 5 mW He–Ne laser. Figure 2 shows the arrangement for taking longitudinal sections.

The laser light needs to be strobed in synchronism with the oscillations. This was achieved by oscillating a suspended mirror with two speakers to produce a reflected Lissajous figure of the laser light on a plate. This plate had a small hole which allowed the light through for a short instant of time in each cycle of oscillation. This strobed light was then swept slowly through the structure by means of a second mirror. The lack of laser intensity prohibited the use of a two-dimensional plano-convex lens to produce a sheet of light. The whole assembly could be shifted laterally so that sections could be taken in different vertical planes.

3. Experimental results

General geometry of structures

By a suitable adjustment of the various parameters mentioned earlier it is possible to obtain coflowing wakes with structures varying from very simple to very complex geometries. Attention will be confined mainly to the simple structures which are produced by very small amplitude oscillations. On first appearance they resemble a 'daisy chain' of interlocking loops which is similar to the 'ladder-like' structure sketched by Achenbach (1974) for the wake behind a sphere. The orientation of these wake structures is influenced by the bouyancy of smoke. In negatively buoyant wakes, where the smoke is heavier than air, the 'loops' always point down. Figure 3(*a*) (plate 1) shows a view of a typical simple negatively buoyant wake structure. Figure 3(*b*) (plate 1) shows a close-up view. Figure 4(*a*) (plate 2) shows figure 3(*b*) on a reduced scale. Figures 4(*b*)–(*h*) (plate 2) show longitudinal sections starting from the wake centre and moving in equal steps towards the near edge. In positively buoyant wakes where helium has been added to the smoke, the reverse occurs and the 'loops' always point up. Figure 5(*a*) (plate 3) shows a typical simple positively buoyant wake. Figure 5(*b*) (plate 3) shows a typical neutrally buoyant wake, when the correct amount of helium has been added to the smoke. In order to lock in this structure, the amplitude of oscillation needed to be larger than in the buoyant cases.

Similar structures occur without artificial disturbances, but they modulate in frequency and amplitude. Figures 5(*c*) and (*d*) (plate 3) show typical unforced negatively and positively buoyant wake structures respectively. These loop-like structures were also encountered in the wakes behind axisymmetric bodies. An experiment similar to that performed by Achenbach (1974) was repeated by the authors, and the unforced wake structure obtained is shown in figure 5(*e*) (plate 3). This pattern corresponds very closely to Achenbach's sketch. The unforced neutrally buoyant wake structure shown in figure 5(*f*) (plate 3) was produced by adding helium to the smoke and passing it over an oblate ellipsoid with its major axis set horizontally across the flow. This body resembles a very thick wing of low aspect ratio and was used rather than an axisymmetric body to help stabilize the orientation so that the plane of symmetry of the structures was normal to the direction of viewing. The velocity of smoke issuing from the tube was adjusted to be approximately equal to that of the outer flow before passing over the above bodies. Such neutrally buoyant wake structures were also observed by Magarvey & Bishop (1961) in the wake behind a liquid drop falling through a second liquid phase. The experimental technique which they used allowed the drop to fall freely with a minimum of gross oscillation, and the wake structures behind the drop as it passed through a second liquid phase exhibited a high degree of symmetry and coherence.

The basic structure obtained in a simple coflowing jet is similiar to that in coflowing wakes except that the loops always point upstream instead of downstream and the expansion with streamwise development tends to be more rapid for the range of parameters used here. Figures 5 (*g*) and (*h*) (plate 3) show two types of neutrally buoyant jet structures.

Figure 6 (*a*) (plate 4) shows a forced positively buoyant jet structure. This bears a striking resemblance to the initial roll-up of cigarette smoke in a still room. Figures 6 (*b*) and (*c*) (plate 4) show cigarette smoke photographed by the authors (see also Brown 1971). This is a positively buoyant jet. A further example of this type of pattern occurs at very high Reynolds numbers, namely in hot smoke issuing from chimneys situated in cross-flow. Figures 6 (*d*) and (*e*) (plate 4) show different views of such a pattern. The large-scale motions resemble the cigarette-smoke patterns and the fine-scale motions of the turbulence do not appear to alter the essential features of the large-scale motions.

Figure 7 (*a*) (plate 5) shows a more complicated jet pattern and figure 7 (*b*) (plate 5) shows a longitudinal cross-section through the jet axis. Figure 7 (*c*) (plate 5) shows a composite photograph of longitudinal sections through the axis of a typical jet. It is made up of several photographs taken 2 min apart and each photograph required 15 s of sweep time of the strobing laser beam. These photographs illustrate the extreme steadiness of these structures and the whole technique of producing these patterns affords a unique opportunity for studying eddying motion in great detail. Figures 7 (*d*) and (*e*) (plate 5) show a very complicated jet structure produced by oscillating the tube with large amplitude (0·5 mm). Although complex, these patterns were extremely repeatable spatially and are completely frozen under stroboscopic light. All the complicated jet structures mentioned above possessed slight negative-buoyancy effects.

Many of the neutrally buoyant jet structures so far mentioned also occur in the absence of artificial disturbances except that they are randomly oriented and modulate in scale. Figures 8 (*a*) and (*b*) (plate 6) are the unforced version of figure 5 (*g*) (plate 3) while figures 8 (*c*) and (*d*) (plate 6) strongly resemble figures 7 (*a*) and (*c*) (plate 5). Because of the erratic orientation of these unforced neutrally buoyant structures, a ciné film was used to capture the patterns when their plane of symmetry was normal to the axis of the camera lens.

In all tests carried out with either jets or wakes, it was found that with strong buoyancy present the orientation of the structures was determined mainly by the buoyancy force and not by the direction of oscillation of the tube. On the other hand, with neutrally buoyant structures the orientation was determined solely by the direction of oscillation.

The vortex pairing phenomenon often reported in free-shear flows was not observed in any of the tests.

Detailed geometry

Consider first the simple structures in coflowing wakes shown in figure 3 (*b*) (plate 1). On close examination one finds that these structures cannot be explained in terms of loops alone. Longitudinal laser sections give further clues to the geometry. Lateral cross-sections, normal to the wake axis, were also made and gave further information. Unfortunately these cross-sections were difficult to photograph. The most crucial information was obtained by viewing the slow-motion images mentioned earlier and watching how the vortex sheets folded up with streamwise development. The sketches in figure 9 show the authors' interpretation. Because of the semi-transparent nature of the smoke, the structures appear in photographs to be more complicated than they really are. Sketches convey the geometry more clearly.

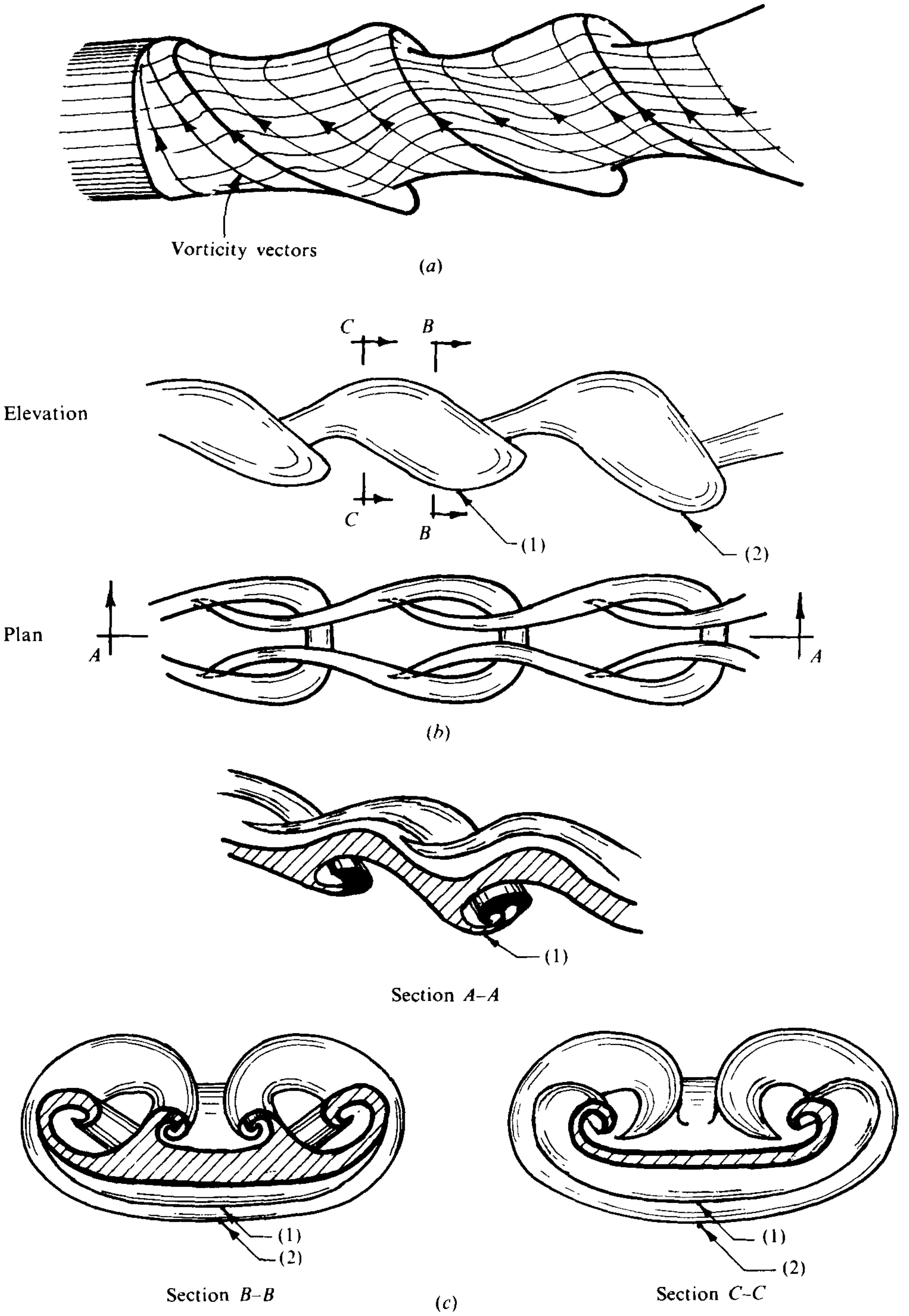


FIGURE 9. Sketches of negatively buoyant coflowing wake. (*a*) Initial instability of cylindrical vortex sheet. (*b*) Rolled-up structure. First angle orthographic projection used throughout. (*c*) Cross-sections. Numbers correspond to points shown in (*b*). Cross-hatching denotes section of original cylinder. Darkened areas shown in section *A*–*A* correspond to cross-sections given in figure 4(*b*) (plate 2).

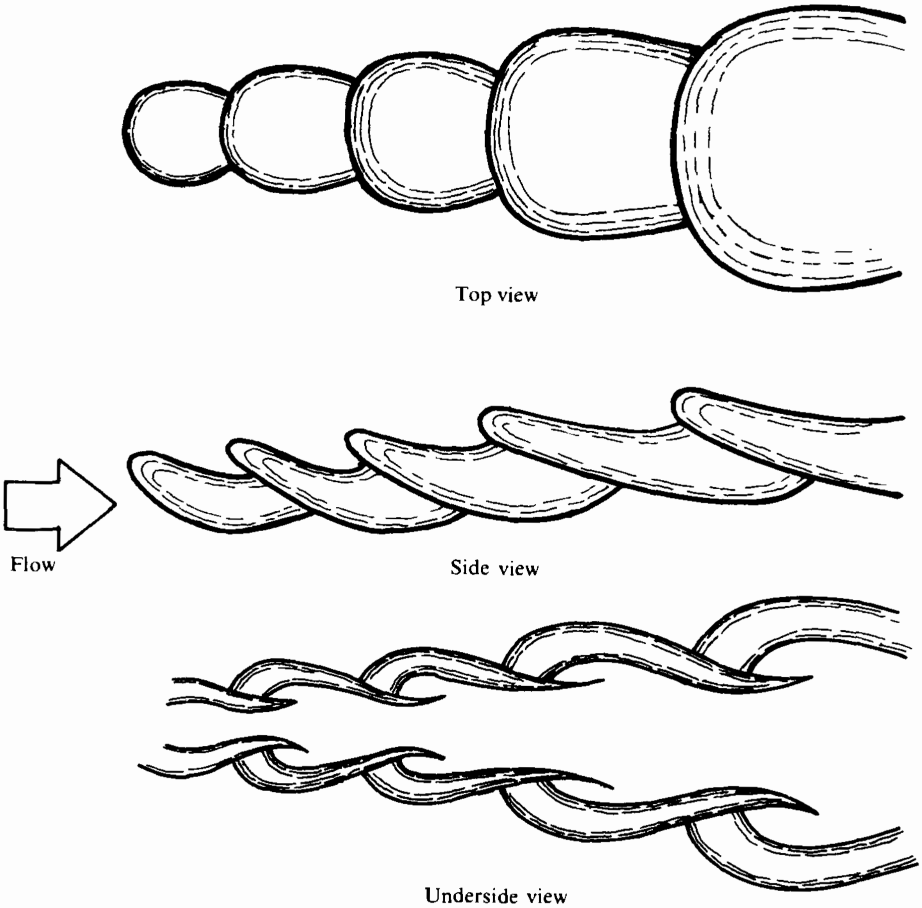


FIGURE 10. Sketches of model representing simple positively buoyant jet.

Figure 9(*a*) shows that the cylinder of smoke can be represented as a vortex tube. There is a slight secondary flow which has been generated by buoyancy forces at the tube exit. This causes the vorticity vectors to be slanted as shown in the figure. Oblique Kelvin–Helmholtz-like instabilities begin to form, causing the vortex tube to develop folds. The best way of understanding the finally developed structure is to manufacture a tube out of wire gauze. The initial pattern illustrated in figure 9(*a*) is very easy to produce. By continuing the folding of the tube one can obtain the structure shown in figure 9(*b*) by curling up the edges of the folds. In fact figure 9(*b*) was produced from photographs of such a wire-gauze model. The various cross-sections shown in figure 9(*c*) illustrate the Kelvin–Helmholtz-like instability quite clearly and are consistent with the laser sections given in figure 4 (plate 2). The interlocking loops are nothing more than the curled-up edges of a series of spoon-like structures or lobes all formed from the one initial cylinder.

The vorticity present in the tube itself, which results from the long length of laminar flow, does not appear to alter the essential features of these structures. A very short tube used in preliminary tests produced similar patterns.

The vortex cylinder does not appear to bifurcate nor do any holes or openings appear. Thus fluid which initially leaves the glass tube remains in this original cylindrical

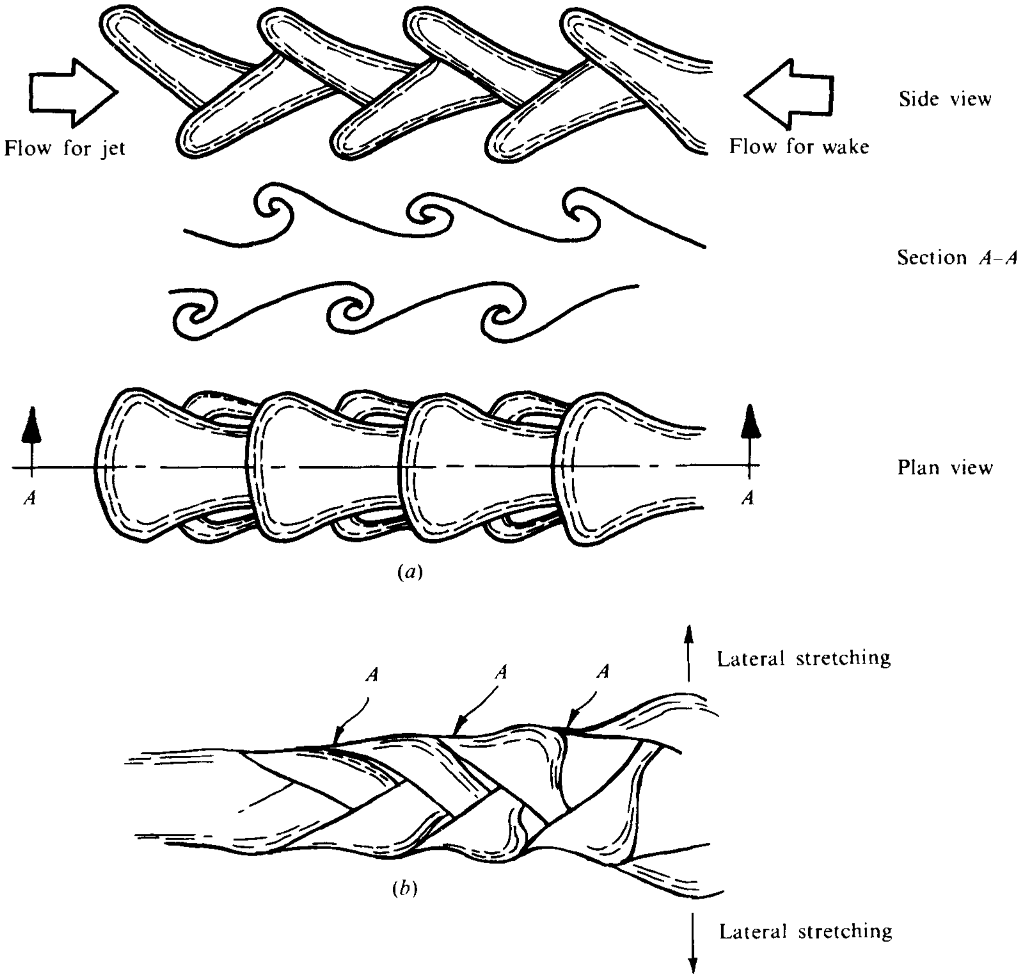
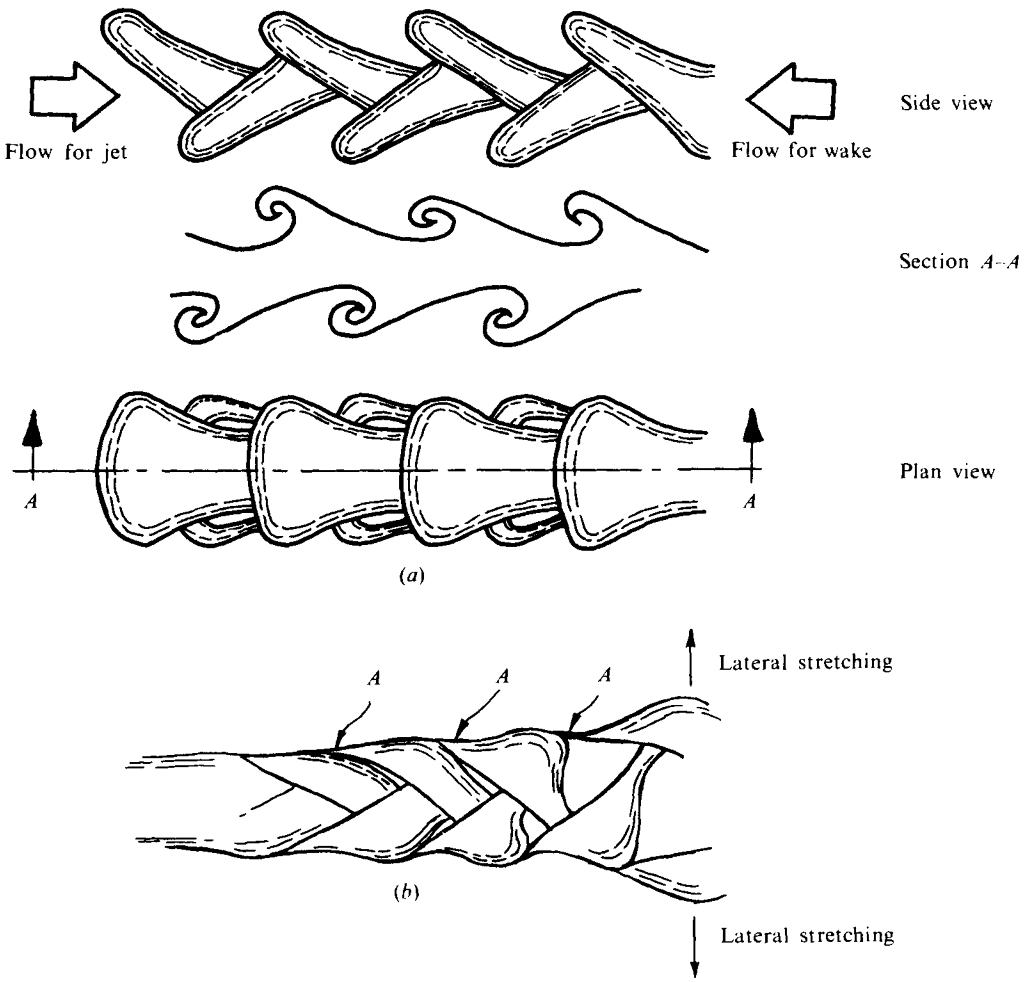


FIGURE 11. (*a*) Projection view of model for simple neutrally buoyant structures. Section A–A shows only the section contained in the sectioning plane. No indication is made of the streamwise development of the spiral roll-up. (*b*) Sketch of a modified version of (*a*) which appears quite often in jets.

boundary. This boundary becomes corrugated and stretched as the structures develop and grow. The laser sections indicate that the vortex cylinder is 'hollow', i.e. smoke appears to concentrate mainly near the boundary of the vortex cylinder.

The geometry of positively buoyant jets is similar to that of positively buoyant wakes except that the lobes point upstream instead of downstream. Also, the jet structures examined here tend to expand more rapidly with streamwise distance than the wake structures. By using wire gauze, a model of the smoke pattern can be made. Figure 10 shows sketches of such a model. This represents the cigarette smoke in figures 6 (*b*) and (*c*) (plate 4) and the chimney smoke in figures 6 (*d*) and (*e*) (plate 4).

Figure 11 shows sketches of a neutrally buoyant jet model constructed from a wire-gauze tube, the flow being from left to right. This pattern corresponds to figure 5 (*g*) (plate 3). If the flow were from right to left this would correspond to the coflowing wake given in figure 5 (*b*) (plate 3). A longitudinal section of this 'double-lobed' pattern



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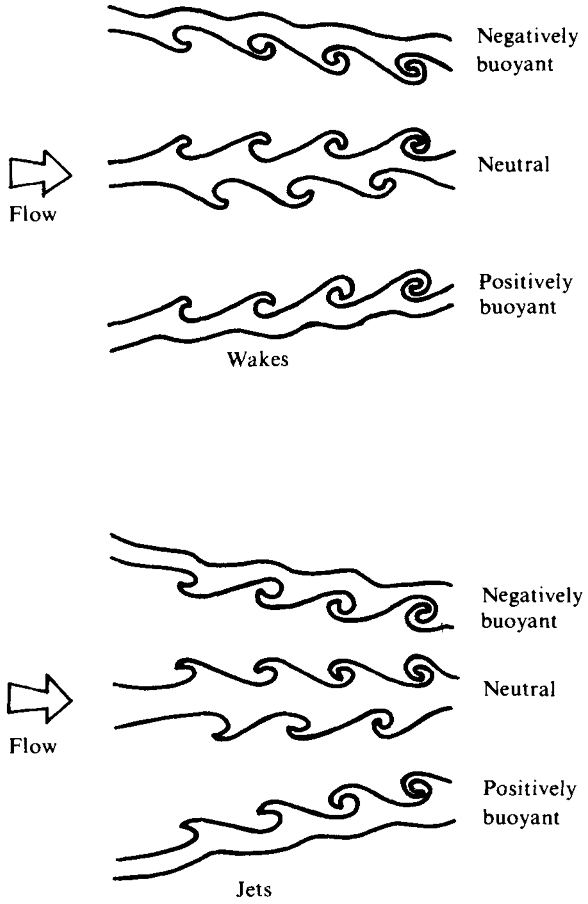

FIGURE 12. Classification of simple coflowing structures. Only sections contained in the centre-plane are shown.

bears a resemblance to the Kármán vortex street patterns reported by Zdravkovich (1969). This model is a three-dimensional version of the Kármán vortex street.

The sketches shown in figure 11(*a*) were deduced from externally illuminated structures. All simple neutrally buoyant structures were slightly unsteady and this prevented the use of the strobed laser beam technique. For very small oscillations of the tube, the pattern shown in figure 11(*b*) was produced, where extra connexions between the lobes appear to occur as shown by points A in the figure (see also figure 5(*h*), plate 3). This structure sometimes rolled up to form the simple structure shown in figure 11(*a*). Under most conditions, it spread rapidly and degenerated into the complicated jet structure shown in figures 7(*a*) and (*c*) (plate 5) with the characteristic mushrooms interconnected with umbilical cord-like strands. Basically, the more complex structures are nothing more than the structures shown in figure 11(*b*) stretched laterally as illustrated, with detailed variations. These depend on flow conditions which the authors have not yet established. The amplitude of oscillation appears to play a part. An unfortunate feature of these neutrally buoyant jet structures is that they are smoke filled (i.e. not 'hollow') and many intricate details cannot be determined.

Buoyant jets tend to spread rapidly in the plane normal to the buoyancy force as illustrated in figure 10.

The simple flow patterns considered so far can now be summarized as shown in figure 12.

4. Further use of technique described

Figures 8(*e*) and (*f*) (plate 6) illustrate the ease with which the detailed velocity field can be investigated and related to the geometry of the smoke structure. The hot-wire trace can be related directly to the photograph of the smoke pattern. The 'pips' shown on the scope screen (figure 8*f*) indicate the anemometer reading which corresponds to the instant shown in figure 8(*e*). By conditionally sampling on the basis of phase a complete instantaneous vector field of velocity could be constructed for each stage of development. The authors are currently experimenting with this technique. Preliminary measurements with a laser-Doppler velocimeter and hot-wire anemometer indicate that the velocity fluctuations are of the order 20 % of the mean flow at about two or three structures away from the nozzle.

The authors also hope to have a movie available of these smoke patterns.

5. Discussion

What is being observed in these experiments is the roll-up and folding of a vortex tube. If the distribution of vorticity in this highly corrugated and distorted tube were known then the velocity field would be known from the Biot–Savart law. Vorticity is probably more concentrated where the smoke appears to be concentrated. Hence, in the case of buoyant structures, the essential features of the flow patterns are two trailing vortices like those behind a wing, the circulation fluctuating along the length of these trailing vortices (see figures 9 and 10). A wing with fluctuating lift might produce a similar effect. Helmholtz' theorems would require the excess and deficiency of circulation to be made up of cross-strands of vorticity interconnecting the two trailing vortices. These cross-connexions would correspond to the cast-off vortices produced by the fluctuating lift. These connexions are of two types. One is a concentrated strand or tube of vorticity and the other is a less concentrated 'veil' which is barely visible. These alternate in the streamwise direction and possess net vorticity of opposite signs. Thus a ladder-like pattern is produced.

Quite often the cross-connexions are not visible, and the flow has the appearance of splitting into two trailing vortices. In fact, Turner (1960, 1973) mentioned this apparent splitting of a 'bent over' plume from a chimney and suggested a model for this flow which incorporated two trailing vortices. The neutrally buoyant simple structures resemble Kármán vortex streets, in the case of both jets and wakes. In fact, if the structures shown in figure 11(*a*) were stretched laterally normal to the plane of symmetry, i.e. if they were issuing from a high aspect ratio rectangular tube, the resemblance to the classical two-dimensional Kármán vortex street would increase. See Chanaud & Powell (1962), who studied two-dimensional jets.

It can be seen from the work described in this paper that coherent structures often encountered in nature are not necessarily the result of the growth of initial infinitesimal disturbances as used in classical linearized hydrodynamic stability theory. Quite often the initial naturally occurring disturbances are large, for example the self-sustained oscillations of the flows about blunt bodies. Here the 'initial' disturbance to the wake is large and results in structures resembling a Kármán vortex street. These remain coherent for long distances.

In the light of these experiments, the large-scale structure of turbulence could perhaps be simulated on a computer by a judicious choice of vortex lines and loops. Landahl (1978) and Leonard (1978) have demonstrated that a most promising technique for the computation of wakes behind spheres is to use a series of vortex rings. The authors suggest that vortex loops may be more appropriate.

6. Conclusions

A technique has been found for producing perfectly periodic structures which are coherent over large streamwise distances in a three-dimensional situation, namely in coflowing jets and wakes. A method has been developed for taking detailed sections of these structures using a strobed laser beam. A likely geometry for coflowing wakes is suggested. It appears that the simple coflowing wakes form a cylindrical vortex sheet which remains continuous and rolls up to form a series of interlocking 'lobes' and that Kelvin–Helmholtz-like instability causes these 'lobes' to roll up at the edges to give the appearance of loops. The orientation of these loops is strongly influenced by the buoyancy forces. In negatively buoyant wakes, the loops always point down, whereas in positively buoyant wakes, the loops always point up. However, in the case of a neutrally buoyant wake, upward- and downward-pointing lobes are produced alternately, giving a three-dimensional structure with geometrical properties similar to the two-dimensional Kármán vortex street.

In the case of simple coflowing jets, the basic structure is similar to that of coflowing wakes but with the 'lobes' pointing upstream instead of downstream. In addition the buoyant jet spreads rapidly in the plane normal to the buoyancy forces. In the neutrally buoyant case the jet spreads rapidly in the plane containing the disturbing oscillation and the pattern degenerates rapidly into a rather complex structure consisting of interconnected mushrooms.

The similarity that exists between the basic structures of jets and wakes enables one to approach the study of these flows in a unified manner. A preliminary classification of these jet and wake structures is made at least for the simple cases. An important outcome of this investigation is that many of these artificially produced structures have been observed in 'natural' situations even at Reynolds numbers well beyond the range used in the artificial flows.

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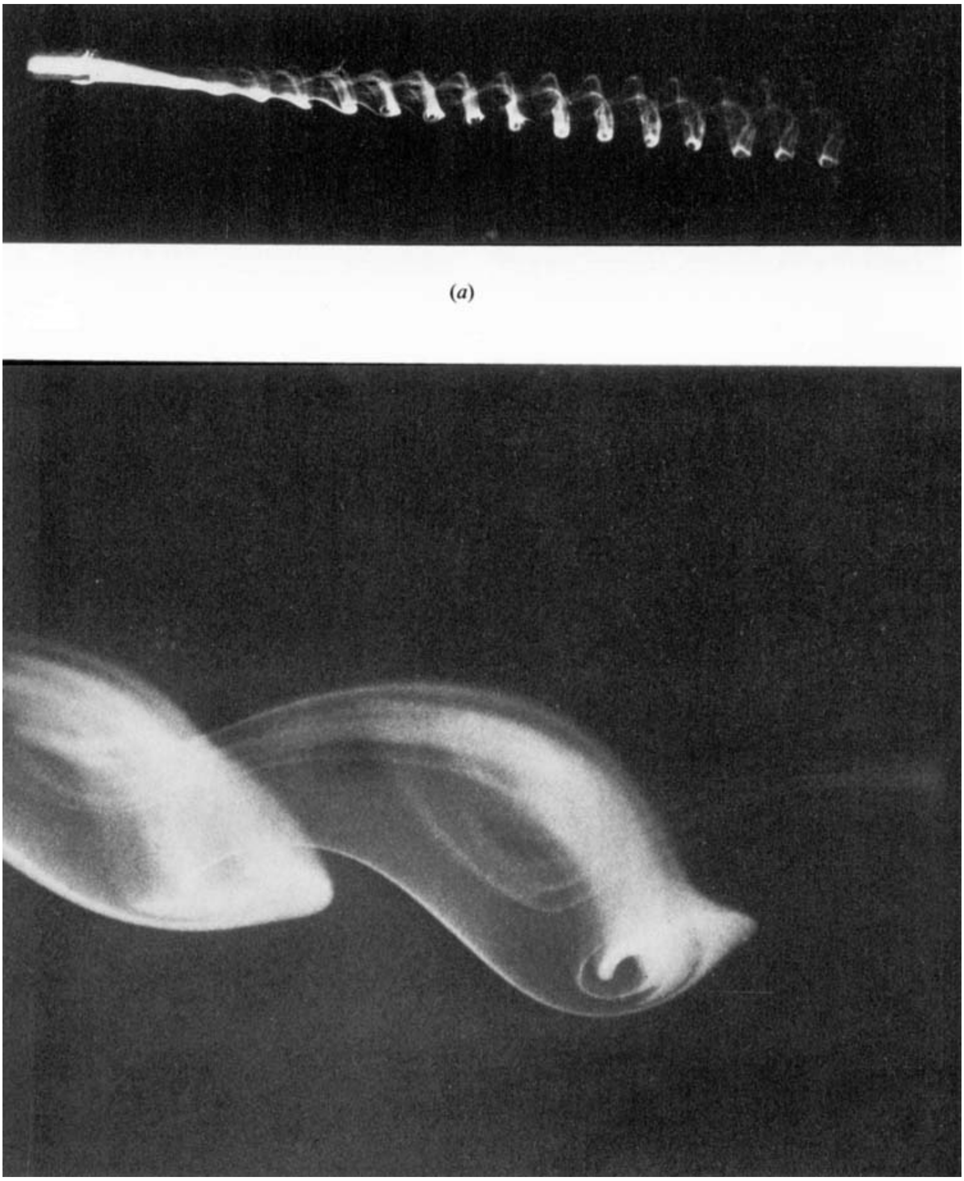
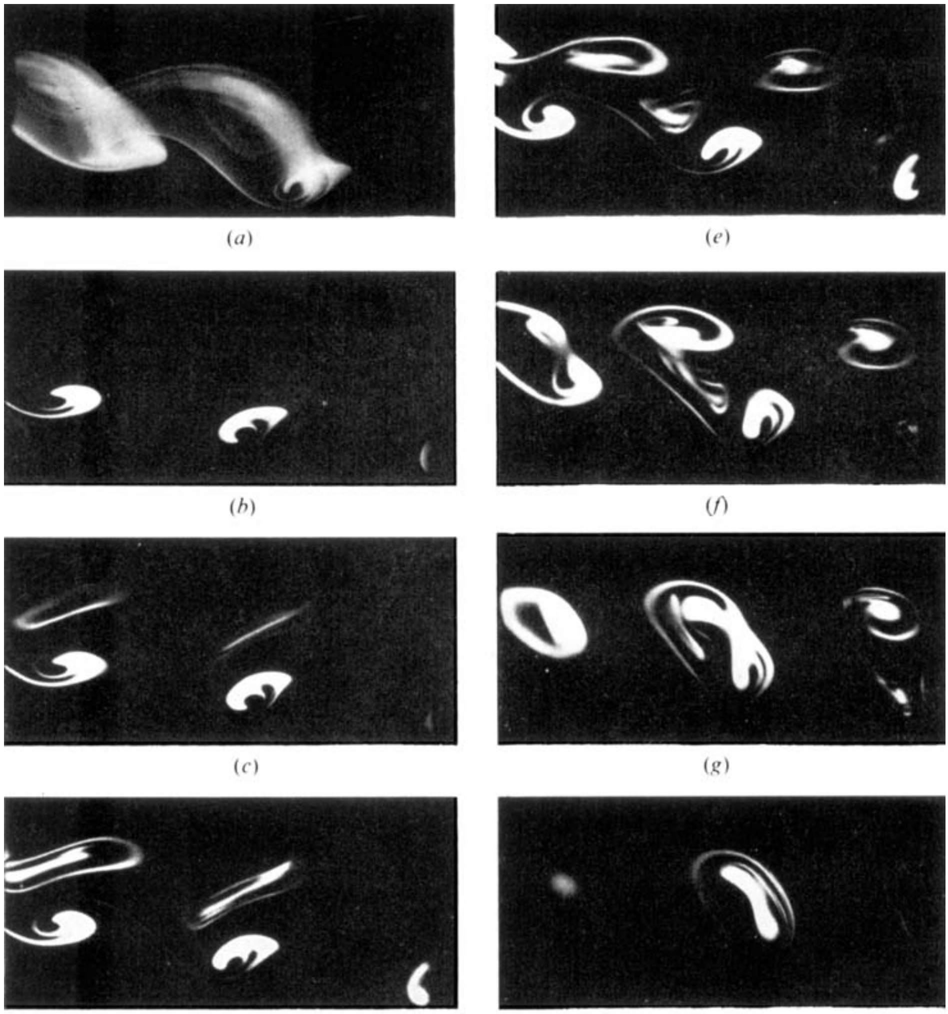


(*a*)

(*b*)

Figure 3. Coflowing wakes. (*a*) Typical simple negatively buoyant wake structure. (*b*) Close-up view of another typical wake which is shown in detail in figure 4 (plate 2). All structures are forced.


(*a*) (*e*)

(*b*) (*f*)

(*c*) (*g*)

(*d*) (*h*)

FIGURE 4. Simple negatively buoyant coflowing wakes, forced. Reynolds number based on outer flow velocity and tube diameter $Re = 350$, frequency of vibration $f = 8$ Hz. Velocity of exit from tube very low. (*a*) Externally illuminated by stroboscopic light. (*b*)–(*h*) Laser longitudinal sections of (*a*) starting from wake centre and moving in equal increments towards near edge. Time of sweep of laser = 15 s.

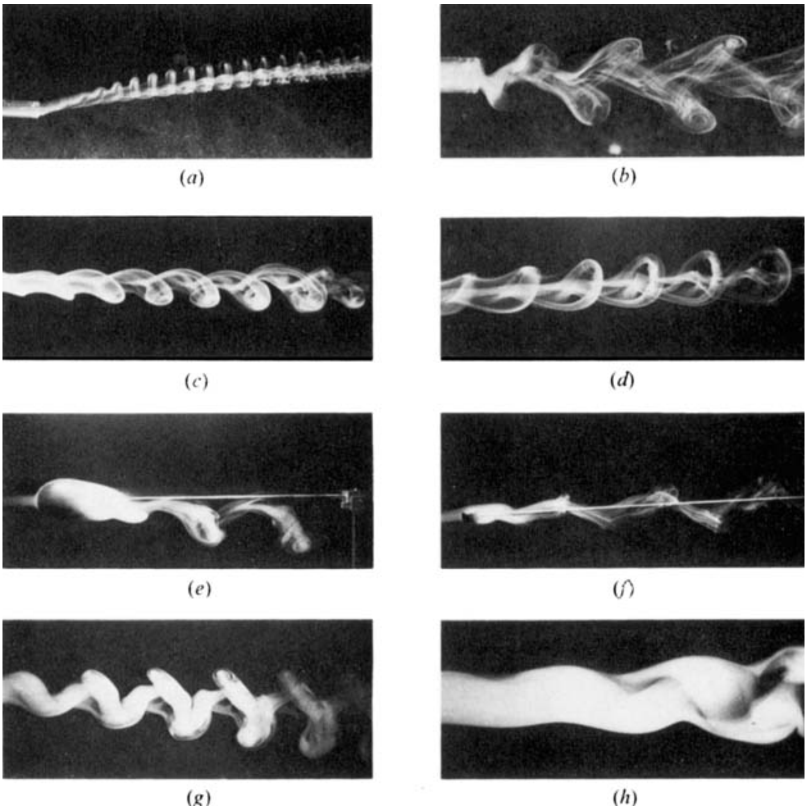
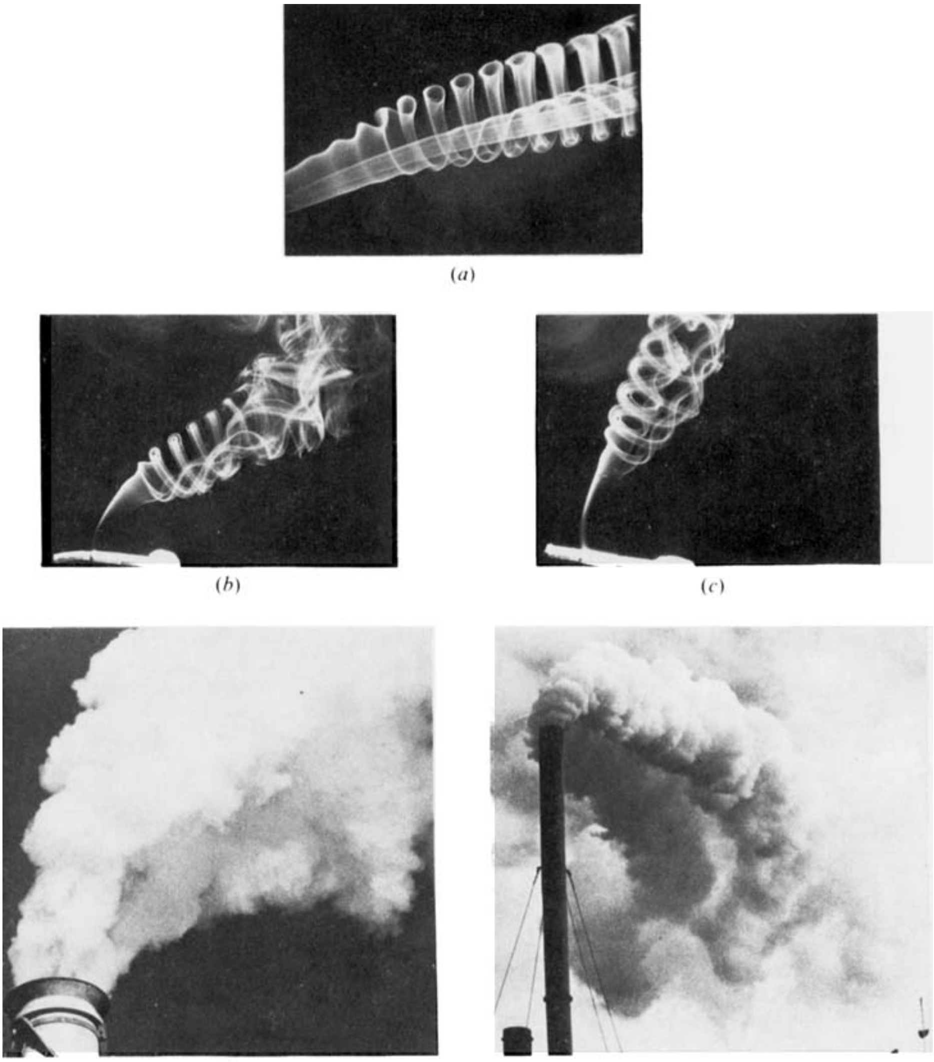


FIGURE 5. (*a*) Simple positively buoyant wake, forced. (*b*) Simple neutrally buoyant wake, forced. (*c*) Unforced negatively buoyant wake. (*d*) Unforced positively buoyant wake. (*e*) Wake structure behind an ellipsoid. In this case smoke corresponds to boundary-layer material leaving body. Also wake is negatively buoyant. No external forcing. (*f*) Neutrally buoyant wake structure behind an oblate ellipsoid. No external forcing. (*g*) Simple neutrally buoyant jet, forced. (*h*) More complicated neutrally buoyant jet in its initial stages, forced.

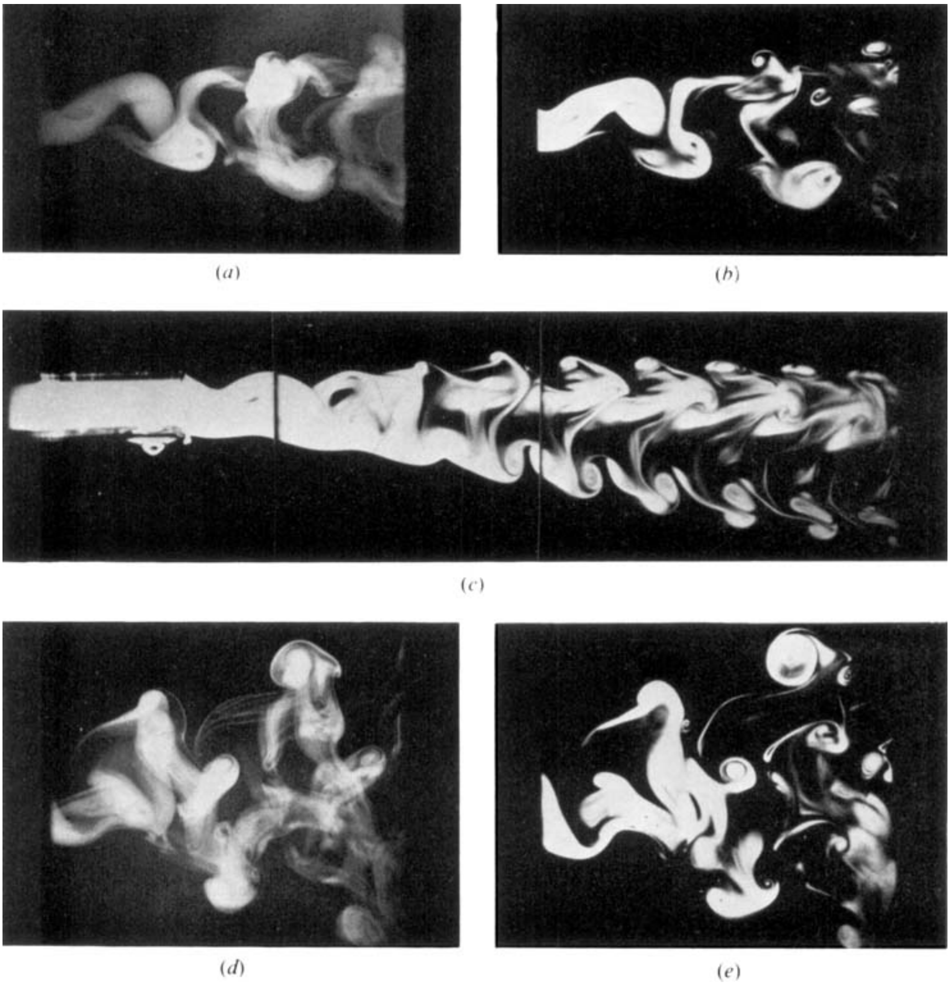


(*a*)

(*b*) (*c*)

(*d*) (*e*)

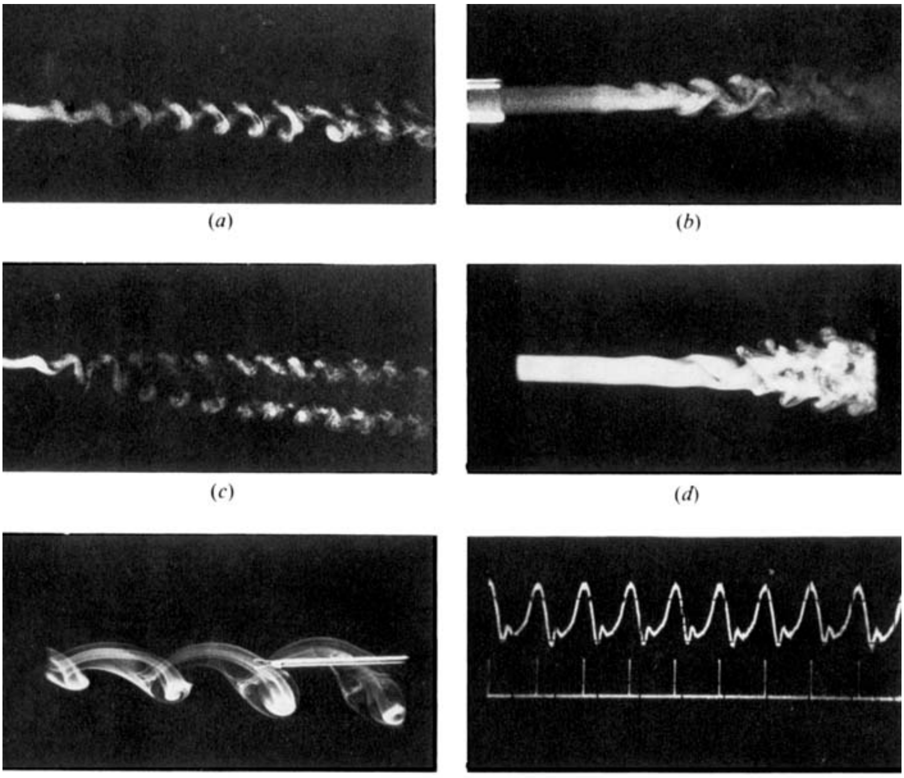
FIGURE 6. (*a*) Simple positively buoyant jet, forced. (*b*) Cigarette-smoke pattern, unforced. (*c*) Different view of another unforced cigarette-smoke pattern. (*d*) Chimney-smoke structure, positively buoyant jet. (*e*) Different view of another example of (*d*).


(*a*) (*b*)

(*c*)

(*d*) (*e*)

FIGURE 7. Complicated coflowing jets. (*a*) Externally illuminated. (*b*) Laser longitudinal section of (*a*) through its axis. *Re* (based on inner flow) = 860, $f = 34$ Hz. Velocity ratio $Q = 2{\cdot}5$. (*c*) Composite photograph of laser longitudinal section of typical jet. $Re = 860$, $f = 30$ Hz, $Q = 2{\cdot}5$. (*d*) Very complicated jet structure, externally illuminated. (*e*) Laser longitudinal section of (*d*). $Re = 1000$, $f = 13$ Hz, $Q = 3{\cdot}25$. All structures are forced.



(*a*) (*b*)

(*c*) (*d*)

(*e*) (*f*)

FIGURE 8. (*a*) Unforced simple neutrally buoyant jet. (*b*) Close-up view of another unforced simple neutrally buoyant jet. (*c*) Unforced complicated jet. (*d*) Unforced complicated jet, showing its initial stages of spreading. (*e*) Hot wire in typical wake. (*f*) Oscilloscope trace corresponding to (*e*).