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ABSTRACT

Experimental results are presented describing the flow field surrounding the potential core of a circular water jet in the Reynolds number region between 5,000 and 15,000. This field is divided into three regions: 1) the shear layer instability zone; 2) the vortex interaction region; and 3) the zone of higher order instability mode and turbulence generation. It is shown that the origin of the large scale structures just downstream of the potential cone can be traced to the upstream vortices, but their statistical behaviour (passage frequency, spatial coherence) seems to be independent of the initial shear layer instability.

INTRODUCTION

In the past, studies of turbulent jets have been restricted primarily to flow regions where certain mean quantities behave independently of initial conditions. Depending on the particular criterion chosen, these so-called self-preserving regions start anywhere from 15 to 50 diameters downstream of the nozzle. There is some evidence that in self-preserving turbulent shear flows in free shear layers as well as in boundary layers, large scale structures exhibit similar behaviour to that in the developing stages of the flow. For this reason, as well as for the fact that in the aerodynamic noise problem the initial development of a jet in the first ten to twenty diameters plays a most important role, considerable effort is being spent on the detailed study of the flow field in and around the potential cone of a jet; see Petersen, Kaplan, and Laufer (1974), Yule, et al (1974), and Fuchs (1972). In this region it is to be expected that two length scales must enter the problem: the initial shear layer thickness, θ , at the nozzle exit, and the nozzle radius, R . As a consequence, the thickness Reynolds number, $\frac{U_{jet}\theta}{\nu}$, will play an important role in the initial shear layer development over a distance depending on the ratio $\frac{R}{\theta}$. Further downstream the flow field scales with the diameter.

Theoretically, the problem was considered by a number of authors, in particular, by Crow and Champagne (1971) and by Michalke (1971). Both formulated the problem in terms of spatial or temporal instability waves over a cylindrical shear layer seeking modes of highest amplification. Michalke took the shear layer finite thickness and spatial wave growth into account but cast the problem within the framework of a linear theory. Crow and Champagne (1971), on the other hand, considered the stability of a uniformly thin jet column and attempted to explain their experimental findings in terms of a combined effect of linear amplification and non-linear saturation of the instability waves.

Although these approaches show some qualitative agreement with observations, they must be critically examined in view of subsequent experimental evidences. In particular, measurements show that the laminar instability waves, after reaching a certain amplitude, breakdown and form rings or helical vortex structures. Incidentally, during this process the centerline r.m.s. velocity fluctuations increase uniformly. The vortex rings interact with each other by coalescing, and during this process the vortices become turbulent. It is most unlikely that such a complicated flow could be cast within a wave instability framework.

A quantitative, experimental study of this problem is equally difficult. Conventional, statistical measurements do not reveal the details of the flow. This is so, partly because the secondary motions, especially in the turbulent regions, are relatively weak and difficult to measure, and partly because they appear randomly over a stationary probe; therefore difficult to detect and to study their behaviour. As a matter of fact, no satisfactory technique has been devised yet that completely overcomes these problems. However, Crow and Champagne (1971) did develop a useful method that was also used in our laboratory. This consisted of subjecting the jet column to periodic disturbances, introducing them upstream of the nozzle, and observing the response of the flow field.

The experimental findings presented in this paper indicate that during the early development of the jet there are three flow regions that can be clearly distinguished provided the ratio $\frac{R}{\theta}$ is sufficiently large at the nozzle exit: 1) the instability region of the initial shear layer in which the distributed vorticity in the layer develops into "lumps" of vorticity; 2) the vortex interaction region along the potential core; and 3) generation of higher modes of instability and turbulence. Each of these regions will be discussed in some detail in the following sections.

EXPERIMENTAL SET-UP AND PROCEDURE

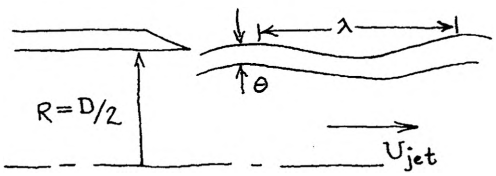
The water jet consisted of a stilling chamber and detachable nozzle (Fig. 1). The axisymmetric nozzle has a contraction ratio of 16:1 and an exit diameter of 1.5 inches. Jet exit velocities ranged from above 5 inch/second to 15 inch/second -- the corresponding jet Reynolds numbers were 5,000 - 15,000. The turbulence level was measured on the jet centerline just upstream of the nozzle exit with a hot-film anemometer. The rms longitudinal fluctuation was about .005 U_{jet}, at a jet speed of 5 inch/second, and was somewhat lower at higher jet speeds. A schematic of the entire jet apparatus is shown in Figure 2. In operation, the jet is immersed vertically in a large tank. Flow rate through the jet is monitored by a Fischer-Porter flow meter. The jet is supplied by gravity feed from a second tank overhead. The supply tank is fitted with an overflow tube and a pump return from a lower sump to maintain constant supply head. When desired, artificial disturbances could be introduced by periodically constricting the jet supply tube.

The flow was visualized in either of two ways. Dye could be introduced at the top of the stilling chamber to color the entire jet column, or could be introduced into the nozzle wall boundary layer through a series of fine slots to color only the region of high vorticity. The dye used was common red food coloring. It is a convenient coloring agent because it can be removed with ordinary laundry bleach -- Clorox, for example. After each injection of dye, the tank could be cleared of color in a few moments -- thus, eliminating the time consuming task of draining and replacing the water. Lighting was no particular problem in this case -- still photographs and movie films were made by back-lighting through a translucent screen.

Hydrogen bubbles were also used. A thin platinum wire was placed across the exit plane and pulsed periodically to produce a sequence of lines. By trial and error, it was determined that .002" diameter platinum wire at voltages of about 100v produced the best results. This wire is small enough to give the desired quantity of microscopic bubbles, and yet strong enough to withstand normal use. An axial slice of the jet was illuminated using a commercial spot lamp and a vertical slit. The room must be completely darkened to provide good contrast between bubbles and background. Even so, obtaining enough light is a problem. Shutter speeds were normally 1/250, using a Nikon F camera with f1.4 lens. The Tri-X film was pushed to approximately ASA 3000 by a special developing technique. Photographs of the bubble traces give a good qualitative picture of the jet flow field in the region 0-4 diameters. An example is shown in Figure 3 for a Reynolds number of 5,000. The time increment between bubble wire pulses was 35 msec.

INITIAL SHEAR LAYER INSTABILITY

The initial flow is laminar, but it becomes unstable shortly after leaving the nozzle. The parameters of this instability can be obtained from dimensional arguments. The geometry is sketched below:



Let the scale of the initial laminar shear layer be characterized by θ (momentum thickness), the initial wave length of the disturbance by λ, and the passage frequency of the disturbance by f. If the Reynolds number is large, viscosity is of no direct importance and one may expect that

$$\lambda/\theta = F(R/\theta), \qquad f\theta/U_{jet} = G(R/\theta). \tag{1}$$

The third parameter characterizing the instability, wave phase speed c, can be obtained from the above results, since $c = \lambda f$. Now, if $R/\theta \gg 1$, it may be assumed that F and G are independent of R/θ. Thus,

$$\lambda/\theta = C_1, \qquad f\theta/U_{jet} = C_2, \quad c/U_{jet} = C_1 C_2. \tag{2}$$

The initial momentum thickness is a function of the jet Reynolds number. For the present jet, the relationship is $\theta/D = .98/\sqrt{Re_D}$, so that with Eq. 2:

$$\lambda/D = c_1\theta/D = .98 c_1/\sqrt{Re_D} ,$$
$$f D/U_{jet} = c_2 D/\theta = c_2\sqrt{Re_D}/.98 . \qquad (3)$$

Thus, the frequency is proportional to $\frac{1}{2}$ power of jet Reynolds number, and the wave length inversely. The wave phase speed is independent of Reynolds number.

Michalke (1971) was the first to solve the stability problem correctly by accounting for the finite thickness of the laminar shear layer. His detailed calculations show the above conclusions to be substantially correct for $R/\theta > 25$, with the most amplified wave having approximately,

$$c_1 \approx 32.3$$
$$c_2 \approx .0167 .$$

In actuality, there is a residual dependence upon R/θ not accounted for by setting λ/θ, $f\frac{\theta}{U_{jet}}$ equal to constants as in Eq. (2). Michalke's (1971) exact results (taken from the figures in his paper) for the most amplified wave, are compared with the present experimental results for three Reynolds numbers in Fig. 4 (a,b). The experimental observations include hydrogen bubble visualization and visualizations utilizing dye injected into the nozzle boundary layer. Wave lengths were determined by direct visual observations of still or movie frames. The period of passage, $T = 1/f$, was determined by following wave disturbances, visible in the shear layer, frame by frame from movie film. A large number of measurements are available, and both the mean and median results have been plotted. The measured results and the theory are in reasonable agreement. No experimental results are given for the Strouhal number corresponding to the highest Reynolds number tested. It was not possible in the movie films of the dyed jet to observe the growing disturbances sufficiently near the nozzle exit where their linear behaviour could be ascertained. (The point where non-linear interactions begin, of course, scales with the wave length or spacing between cores and, hence, occurs much sooner at higher Reynolds numbers.) Even at Reynolds number of 10,000, there is a large difference between the mean and median frequencies of passage. This is a reflection of the beginnings of a pairing. As pairing is approached, the time interval between vortex passages becomes small and the frequency of passage becomes correspondingly large. The average frequency is heavily weighted by these high frequencies, whereas the median is more nearly characteristic of the largest time intervals between vortices.

Michalke's (1971) theoretical results show very little difference in the maximum amplification rates between the axisymmetric mode ($m = 0$) and the lowest mode with azimuthal dependence, $m = 1$. (There may, indeed, be slight differences, but at $R/\theta > 25$, it is impossible to distinguish between the theoretical curves presented.) Observations indicate that at $Re = 5,000$ ($R/\theta \cong 36$) the disturbances are almost always axisymmetric, leading to the formation of donut shaped vortices. At larger Reynolds numbers, (10,000 and 15,000) the vortices rapidly develop azimuthal dependence. Rings with between 4—8 or 9 lobes are commonly observed. This structure is probably a result of non-linear processes. At a Reynolds number of 15,000 however, the vortex core does appear to be helical in form - corresponding to the $m = 1$ mode - for, perhaps, 50% of the time.

VORTEX INTERACTIONS ALONG THE POTENTIAL CORE

The pairing interactions which occur between axisymmetric vortex rings can be described as follows: the downstream ring slows perceptably, and grows slightly in diameter under the influence of the approaching upstream ring. The upstream ring, in turn, increases its speed and decreases its diameter until the two merge to form a single, large ring. The paths of two typical vortex cores undergoing pairing are shown in Figure 5. The pairing of adjacent vortex rings can be viewed as the consequence of a secondary instability: a row of equally spaced vortex rings of equal strength are in dynamically unstable equilibrium. For, if any one vortex is displaced slightly, it is clear that it must proceed toward its nearest neighbor until a pairing occurs: the upstream ring, which squeezes through the downstream ring, is always trapped, and the vorticity of the two rings merge.

Position-time information taken from successive movie film frames allows the calculation of velocity also. In Figure 6, the axial velocity is shown as a function of X/D for a typical vortex interaction. The size of the data increments is shown on the figure, and the accuracy of the velocity trajectories is judged to be about $\pm$ 10% of the jet velocity. At $X/D < 1$, both vortices have a speed near half of the jet velocity. At about $X = 1\frac{1}{2}D$, there is a rapid change in velocity. The reason for this increase and decrease in velocity is thought to be associated with the formation of the finite amplitude vortex from the initial instability. The pairing interaction extends from about $X/D = 2$ to $X/D = 3$. The downstream vortex, with velocity $\cong .5\ U_{jet}$ at the beginning of the interaction, slows to about $.38\ U_{jet}$; while the upstream vortex attains a maximum speed of approximately $.9\ U_{jet}$. After merging, the combined ring has a speed $.63\ U_{jet}$ which exceeds the speeds of the original members.

At higher Reynolds numbers, when the helical mode (m = 1) dominates the instability, the interaction between adjacent portions of the vortex core are more complicated, but there is still a strong tendency to form large vortex structures which are roughly axisymmetric. In this process, portions of the helical core draw closer together to form rings, while other portions of the core are simply stretched. This is schematically illustrated in Figure 7. A side view of the jet is shown; crosses connected by a light dotted line indicate the path of the helical vortex core before interaction. During interaction, the vortex core is deformed as shown by the solid lines. Hatched circles represent the intersection of the core with the right and left extremities of the jet. Figure 8 shows idealized x-t traces illustrating the fundamental interactions in the m = 0, m = 1 cases. The first case (m = 0 mode) represents axisymmetric pairing, to produce a spacing roughly twice the original spacing. For the m = 1 mode interaction, paths of both the right and left sides of the vortex core are traced in time. This interaction produces a spacing roughly 3/2 larger than the original spacing. Examples of actual vortex paths obtained from movie films are shown in Figure 9(a,b). It is clear that many variations of the interaction just described can occur.

The most important consequence attributable to these vortex interactions is the production of large scale features -- at the termination of the potential core -- which are relatively insensitive to variations in Reynolds number. In order to demonstrate this point, the paths (x-t traces) of 20 to 60 individual vortices were followed along the potential core ($X/D<4$) for the three Reynolds numbers: 5, 10 and 15 thousand. At each selected downstream position, the passage periods between successive vortices were used to define a vortex passage frequency, or Strouhal number. The results for each individual passage are shown plotted in Figure 10 for a jet Reynolds number of 5,000. At $X/D = 1$, the mean or average Strouhal number is 1.25 (the median is slightly less) and this value describes the initial laminar instability. There is a band-width, or frequency spread, associated with the instability of about ± 50% (of the mean frequency). Only slightly farther downstream however, the bandwidth is considerably increased. The reason is that during pairing, the frequency of passage of adjacent vortices can become extremely large (corresponding to small spacing). The average frequency, at locations where pairing can occur, is heavily weighted towards high frequencies. But for every pair of vortices which draw close, there exists a second pair which increase in relative spacing. Their passage frequency or Strouhal number is decreased -- but at most by a factor of two. The median frequency, or Strouhal number, is a good measure of this progression to lower frequencies (larger length scales). At $X/D = 4$, the median Strouhal number is $\approx .5$, and indicates that slightly more than one pairing -- 1.4 pairings on the average -- has taken place upstream.

Figure 11 shows the median Strouhal numbers plotted versus X/D for three Reynolds numbers which differ by a factor of three. (At the highest Reynolds number, the vortices become too diffuse to follow accurately beyond $X/D = 2$.) The results lie roughly on a single curve, and give important evidence that the large scale, vortex structure of the jet reaches a terminal state, $St \cong .5$ at $X/D = 4.$, which is independent of the Reynolds number or the initial frequency of instability.

GENERATION OF TURBULENCE

The large scale vortical interactions -- the result of inhomogenities in the initial vortex strength and spacing -- occur randomly distributed in time and position along the potential core. If one simply explores time history at a point, the flow appears less organized than it really is, for the spatial coherence of the structure at any instant is ignored. But any truly turbulent flow must contain a random distribution of vorticity at much smaller scales, as well. There appears to be a definite sequence of events which lead to the production of a small scale, random vorticity field. The observations leading to the present conclusions were made at a Reynolds number of 5000, where the initial instability is primarily axisymmetric. The conclusions are probably equally valid at higher Reynolds numbers, although the appearance of the m = 1 mode may introduce additional complexities.

The vortex cores which form from the initial laminar instability develop high mode azimuthal structure. A typical example is shown in Figure 12, where the vortex ring core, viewed from slightly above, is seen to contain waves with a mode number of about 9 (see, for example, Widnall, et al (1974)). Maxworthy (1974) has concluded that an isolated ring will eventually develop a turbulent core as the result of the growth of azimuthal waves. This breakdown may occur in a violent manner with much debris (vorticity) left behind. Thereafter, turbulent material is continually torn from the core and deposited in a downstream wake. The vortices along the potential core do not possess a wake - indeed the presence of a wake is inconsistent with the existence of a potential core region. In this case, vorticity is shed primarily as a result of the pairing interactions. Figure 13 shows a sequence of 3 photographs taken at various stages of the pairing process looking up the axis of the jet. (A hydrogen bubble wire was placed around the circumference of the jet, 1/16" downstream of the nozzle exit. Bubbles produced at the wire are swept into the cores of the vortices which appear in these photographs as bright, segmented rings. Bubbles were not generated around the complete circumference of the jet, but only in segments. The presistence of these segments indicate the absence of azimuthal velocity in the cores.) The first photograph shows the ring upstream of the point of interaction. Azimuthal structure is barely seen. In the second photograph, the ring has been squeezed to its smallest diameter to pass through the downstream ring. Note the enormous intensification of the azimuthal structure. The final photograph shows that pieces of the (inner) vortex core actually pinch off to form small, individual vortex loops. Some of the loops are left behind as the remainder of the inner vortex core is swept through, and merges with, the outer ring. Most of the detrital vorticity is swept through and discarded after making an almost complete transit of the outer ring. A side view schematic of the process is sketched in Figure 14. Many earlier workers, Crow and Champagne (1971), Yule (1974) have commented on this sheath of (small scale) turbulent fluid which tends to obscure the visualization of underlying large scale structure.

As the vortex rings propagate downstream, vorticity is diffused inward. The potential core is terminated when the vorticity within the rings reaches the axis of the jet. This occurs at approximately 4 diameters downstream. A fundamental change in the character of the vorticity distribution within the rings seems to take place at about the same point. Whereas upstream, the vortices possess recognizable, organized core structure, albeit turbulent; the vorticity now appears much more uniformly distributed. Crow and Champagne (1971) used the term "puff" to describe the structures they observed in the region > 4 diameters downstream. Indeed "puff" is a good descriptor if one keeps in mind that the gross flow field still resembles that of a vortex ring. Figure 15, taken from 16 mm movie film, shows the transition in structure from vortex ring with organized core to puff.

The reason for the loss of a recognizable core is not presently known. Maxworthy (private communication) has speculated that the organized core may not be able to survive in such a high level of ambient turbulence - turbulence produced by the passage of previous rings. This idea is supported by the observation that the initial vortex, in a jet started from rest, does not lose its organized core, although following ones do.

CONCLUDING REMARKS

The visual observations presented here indicate that interactions of finite amplitude vortices are the major feature of the flow in the developing region of an axisymmetric jet. The interactions are complicated and varied -- especially at the highest Reynolds number -- and our description, almost of necessity, is an oversimplification. The most important finding is that the Strouhal number, associated with the passage of large scale features at the termination of the potential core, reaches a value of approximately .5 independent of Reynolds number. (The corresponding length scale is approximately 1.3D if the median vortex speed is taken to be .65 U_{jet}.) Coalescence of vortices to form ever larger structures is the mechanism by which independence from the initial length scale is achieved. Although the present experiments cover a limited range of Reynolds number, it is plausible that the mechanism is operative at higher Reynolds numbers also.

ACKNOWLEDGMENT

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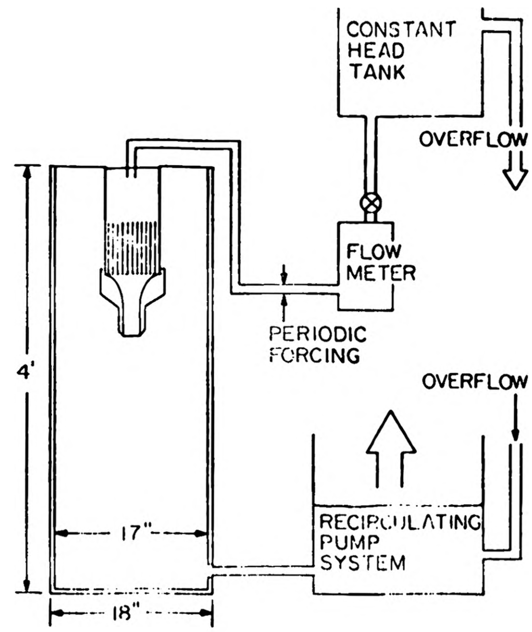

FIGURE 2. SCHEMATIC OF JET APPARATUS.

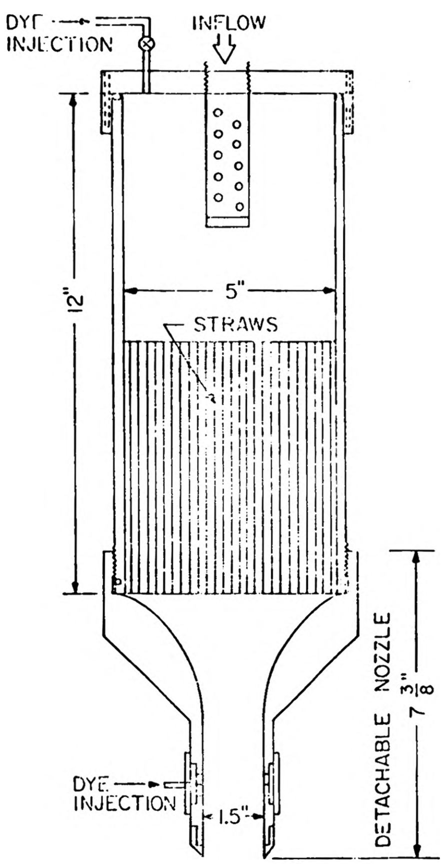

FIGURE 1. THE AXISYMMETRIC JET.

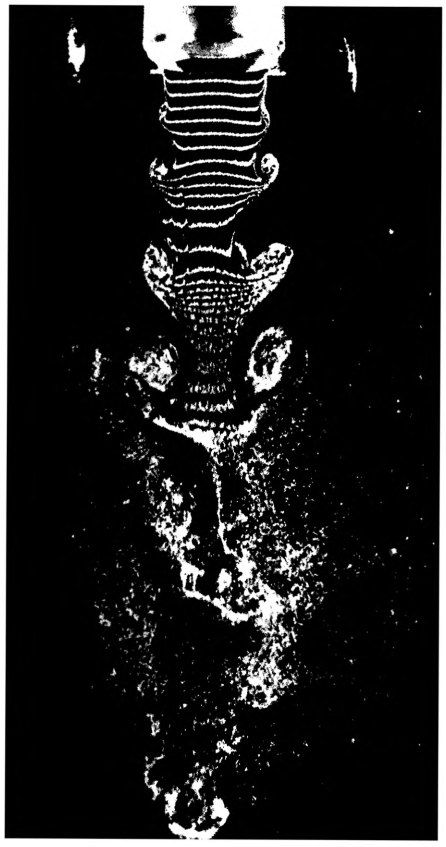

FIGURE 3. VISUALIZATION OF JET USING HYDROGEN BUBBLES. Re_D = 5,000; TIME INCREMENT BETWEEN BUBBLE PULSES = 35 MSEC.

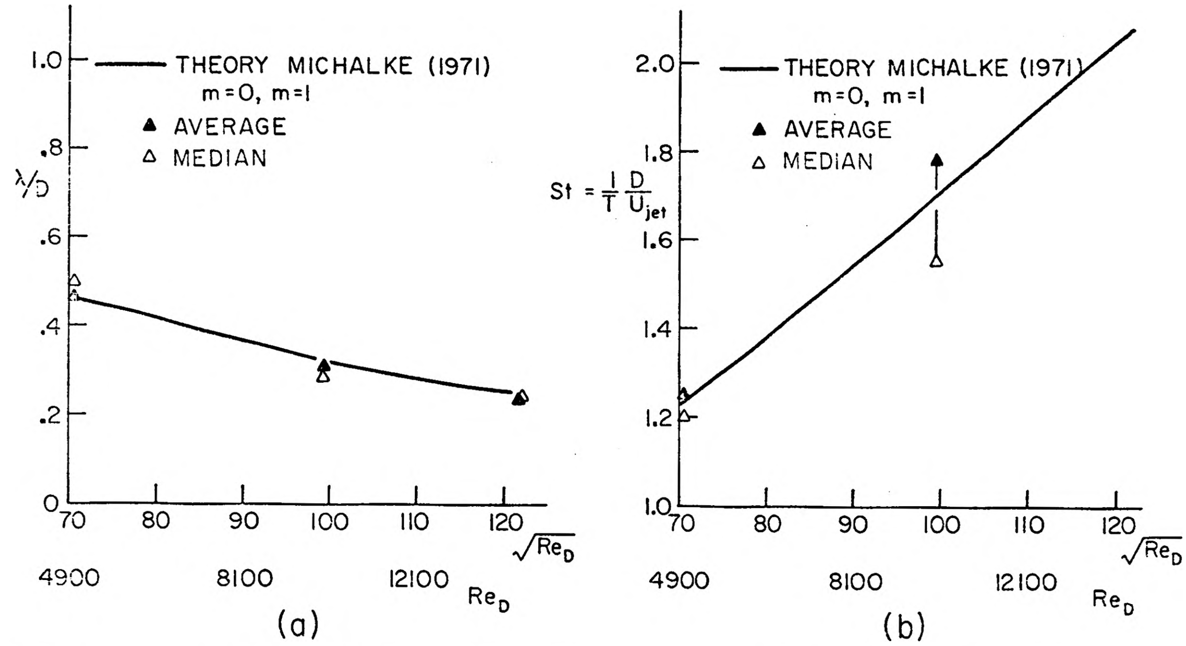

FIGURE 4. (a) WAVE LENGTH OF INITIAL INSTABILITY, COMPARISON OF EXPERIMENT AND THEORY. (b) FREQUENCY OF INITIAL INSTABILITY.

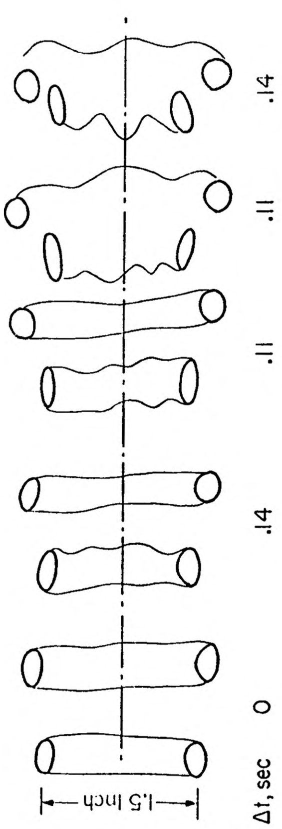

FIGURE 5. THE RELATIVE POSITIONS OF TWO VORTEX CORES UNDERGOING A COALESCENCE OR PAIRING. TIME INCREMENTS ARE INDICATED IN THE LEGEND. Re_D = 5,000.

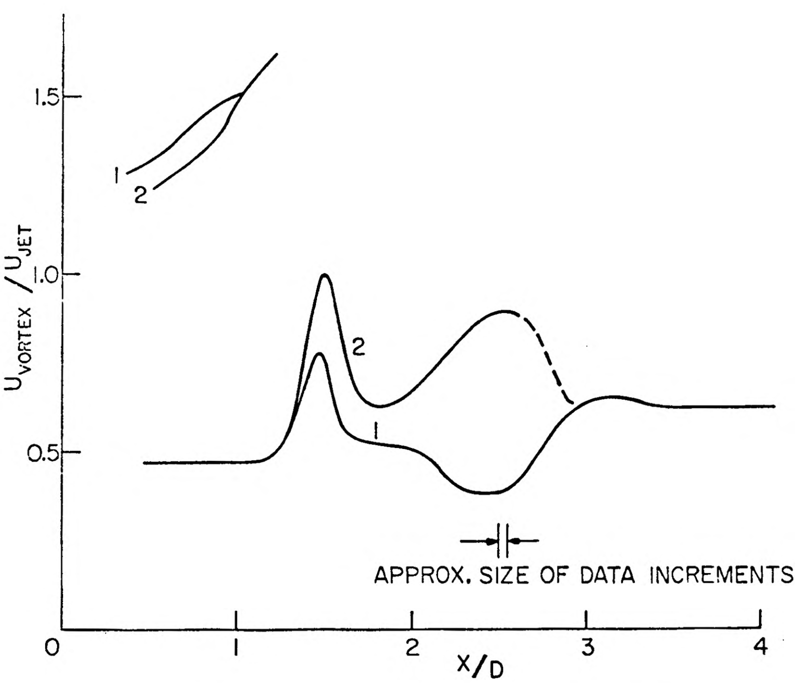

FIGURE 6. AXIAL VELOCITY OF TWO VORTEX CORES UNDERGOING PAIRING. Re_D = 5,000.

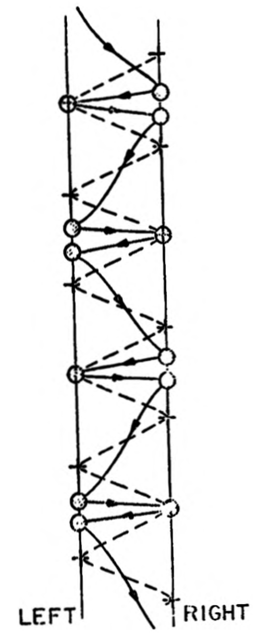

FIGURE 7. SCHEMATIC OF m = 1 MODE INTERACTION. DOTTED LINE BETWEEN CROSSES INDICATES INITIAL HELICAL VORTEX CORE. SOLID LINE INDICATES DISTORTION OF VORTEX CORE DURING INTERACTION. HATCHED CIRCLES REPRESENT INTERSECTIONS OF VORTEX CORE WITH EXTREMITIES OF JET.

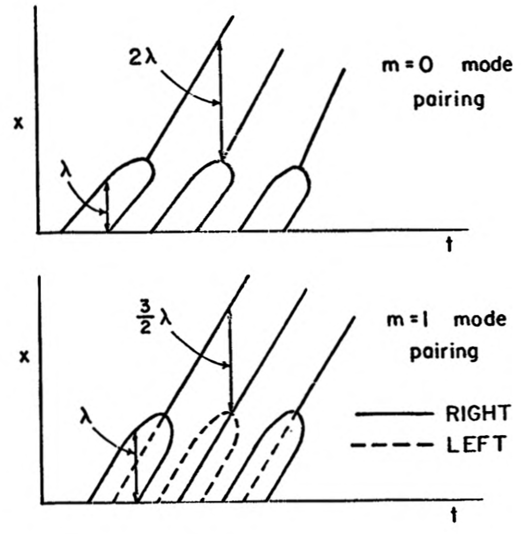

FIGURE 8. THE FUNDAMENTAL VORTEX INTERACTIONS: UPPER, AXISYMMETRIC (m = 0) PAIRING OR COALESCENCE; LOWER, m = 1 COALESCENCE.

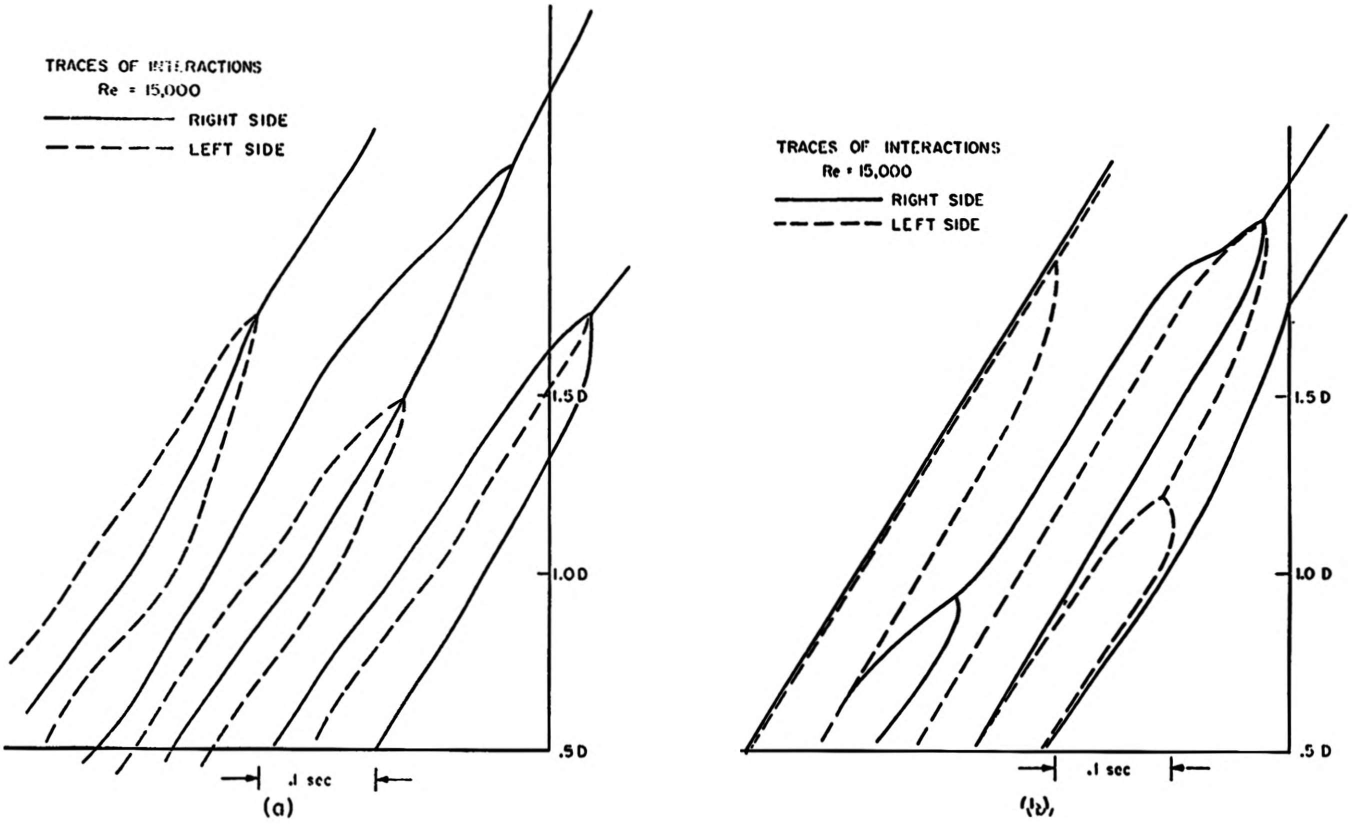

FIGURE 9. VORTEX CORE PATHS OBTAINED FROM MOVIE FILMS; (a) THE FUNDAMENTAL INTERACTION (b) VARIATIONS OF THE FUNDAMENTAL INTERACTION.

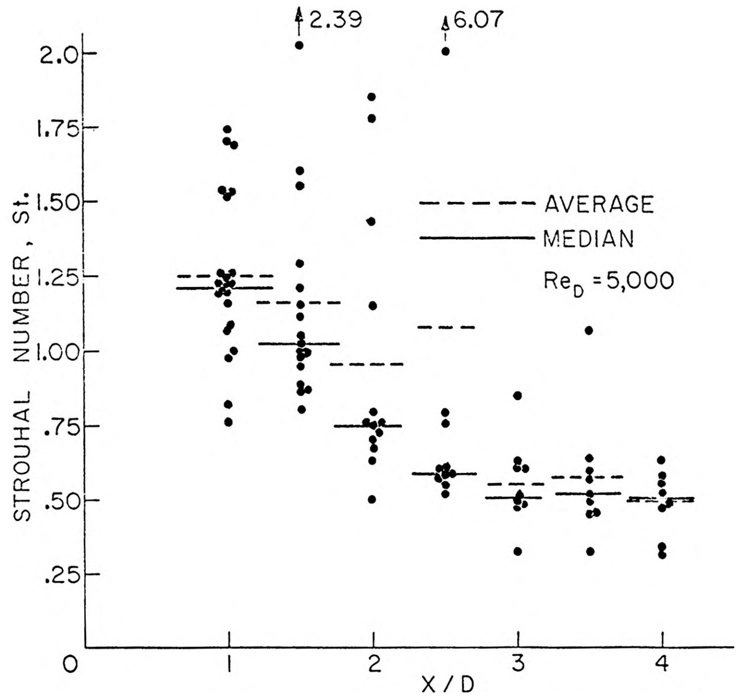

FIGURE 10. THE FREQUENCY OF INDIVIDUAL VORTEX PASSAGES AS A FUNCTION OF DOWNSTREAM POSITION. St = D/TU$_{jet}$, WHERE T IS THE TIME PERIOD BETWEEN ARRIVAL OF ADJACENT VORTICES.

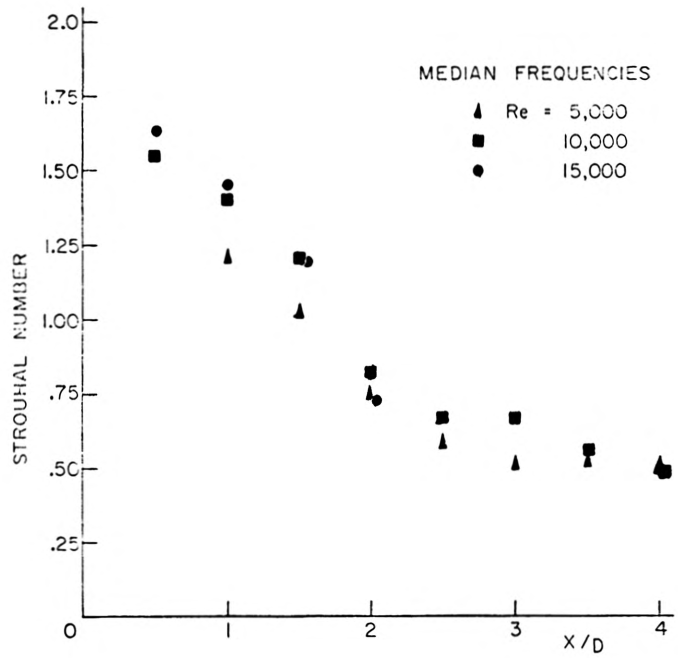

FIGURE 11. THE MEDIAN FREQUENCY (STROUHAL NUMBER) OF VORTEX PASSAGES AS A FUNCTION OF DOWNSTREAM POSITION FOR THREE REYNOLDS NUMBERS.

FIGURE 12. AZIMUTHAL WAVES ON VORTEX CORES AT Re$_D$ = 5,000. IN THE PRESENT PHOTOGRAPH, THE EFFECT IS ENHANCED BY FORCING THE JET SLIGHTLY AT AN EQUIVALENT STROUHAL NUMBER OF 1.6.

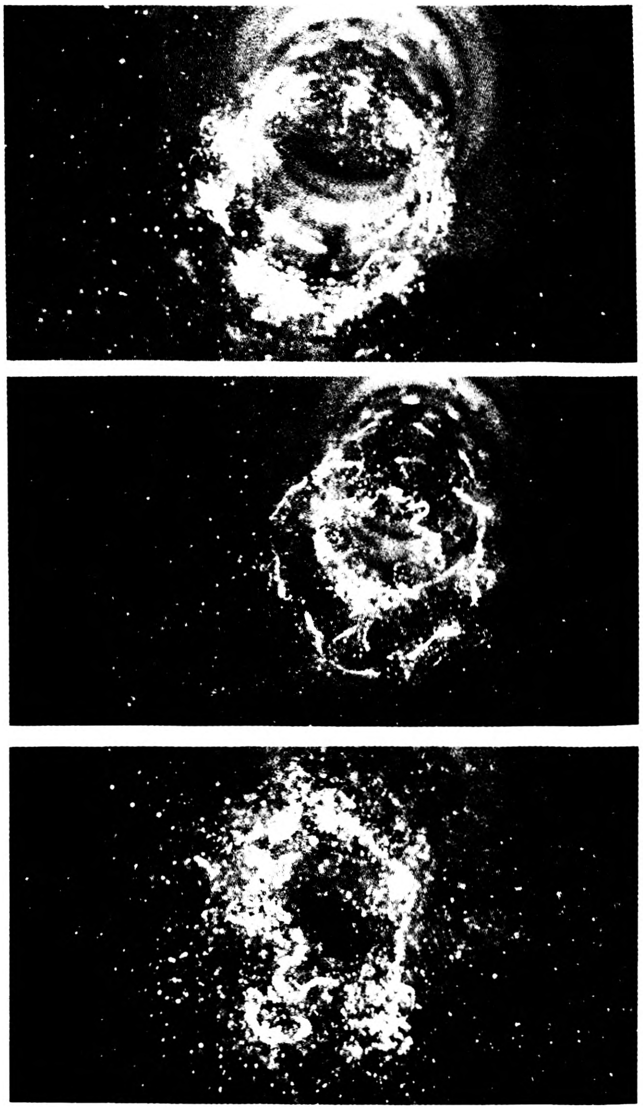

FIGURE 13. AZIMUTHAL STRUCTURE SEEN LOOKING ALONG AXIS OF JET. THE EFFECT IS ENHANCED BY FORCING THE JET SLIGHTLY AT St $\approx$ 1.0: (a) X/D = 1.75; (b) X/D = 2.75; (c) X/D = 3.3.

FIGURE 15. TRANSITION OF RINGS TO PUFFS AT TERMINATION OF POTENTIAL CORE. JET IS FORCED SLIGHTLY AT St $\cong$ 1.0.

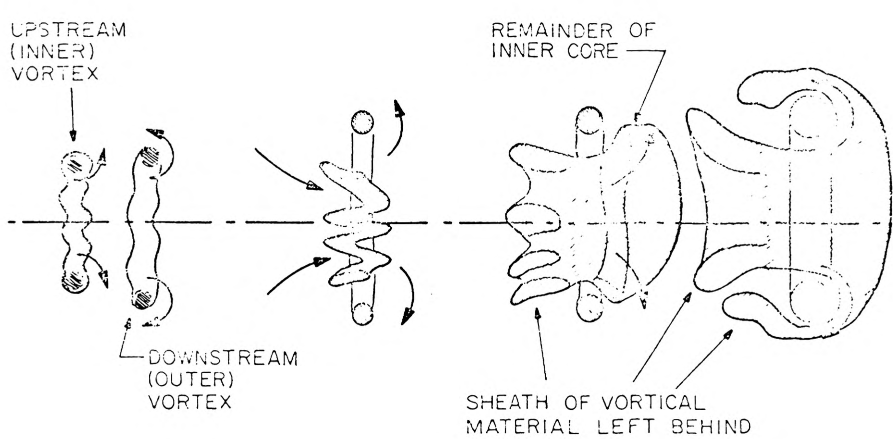

FIGURE 14. SIDE VIEW SCHEMATIC OF VORTICITY SHED DURING PAIRING INTERACTION.

DISCUSSION

A. K. M. Fazle Hussain, University of Houston: I have a number of questions, mostly seeking some clarifications. You have referenced the work of Crow and Champagne; but the Strouhal number that they found or identified as the preferred mode which is capable of producing the strongest near field organized structure over a range of Reynolds numbers was 0.3. How do you explain your Figures 10 and 11 where the data seem to be all above a Strouhal Number of 0.5 vis a vis the data of Crow and Champagne?

Laufer: It is not clear but when you look at the first figure you will see that there is quite a bit of scatter in the data, and it depends on what kind of averaging you do to come up with this number. I think at this stage the interesting thing is not the absolute values of this number but the fact that Crow and Champagne, as well as we, find that such a fixed number indeed exists. We are not at the stage where we really worry about the absolute value.

Hussain: It is my understanding that you conjecture that the phenomenon you observe at the low Reynolds number also occurs at high Reynolds number. Therefore the question arises: what happens if you try to split the near exit boundary layer into two groups viz laminar and turbulent and see if some semblance of vortex ring could be observed with the same Reynolds numbers but with tripping. In other words, is the streamwise dependence of Strouhal number shown in your figures peculiar to the low Reynolds numbers of the flows studied?

Laufer: Actually it is more than just a conjecture. I don't know whether you have had a chance to see the report of the Southampton group. They look at much higher Reynolds numbers in a different geometry, in a two-dimensional mixing layer. Brown and Roshko went up to Reynolds numbers of 10^7 where they can see the same type of vortex interaction, large scale coalescence occurring at very large Reynolds number, as was seen in their earlier work.

Hussain: Since the formation of vortex rings from initial laminar shear layer is due to instability, how can one explain the formation of near shear layer vortex ring formation in an initially turbulent shear layer?

Laufer: I believe that the shear layer, whether in a laminar or turbulent state, undergoes a Kelvin-Helmholz instability which eventually results in formation of vortices.

Hussain: I submit that probably the vortex ring dynamics (even though the data of Brown and Roshko is fairly conclusive as to the nature of the pairing in a shear layer) are quite different and I do not have the explanation. But I would like to inform you that we have done some preliminary circular air jet experiments over a Reynolds number range of 8000 to 130,000 which covers the range of your experiment and also Crow and Champagne, and we have found two interesting things. We found that when the shear layer is tripped (or turbulent), then the preferred mode is 0.3. However, if it is not, at least for the three different nozzle diameters we have tried, the preferred mode seems to be 0.4. These values as well as the Strouhal numbers for stable subharmonic formation are dependent on the initial condition.

Laufer: Those are very exciting results indeed. We find that by forcing we can also localize in a certain sense, the pairing, but we have not for instance, looked at the situation where the initial boundary layer is turbulent.

H. M. Nagib, IIT: Since we see this all as very convincing evidence of the presence of the pairing process, how important is the pairing process to the mechanism of the growth of the shear layer? And would that be related to the spreading rate of the jet?

Laufer: I think it is intimately related; in fact, the finding that the coalescence doubles locally demonstrates this. It is not the only mechanism of the spreading; at the same time one would expect some turbulent diffusion to take place.

Nagib: Is pairing only limited to laboratory jets and shear layers ("clean conditions") or does it also exist in some form in industrial jets and shear layers ("unclean conditions")? If the former is true what are the substitute spreading mechanisms of the layers in "unclean conditions"?

Laufer: Maybe I would not use the word pairing, but rather interaction, since some kind of lower harmonic formation must take place. There is one interesting evidence, not in the jet but in the wake where under certain circumstances the complete absence of the large scales is noted, so that the turbulent laminar interference of the wake is practically a straight line, and the wake has practically a constant thickness. Thus the absence of large scales corresponds to zero growth rate.

Victor Goldschmidt, Purdue University: The folding of the interface may provide another diagnostic tool for what occurs further downstream. The question is, do you believe that we need folding in order to have entrainment?

Laufer: I think part of the entrainment seems to be due to this folding. Again, I don't want to make a strong point on that because our experience at high Reynolds number is very limited, and the situation might be different. But at least at low Reynolds numbers, I think that seems to be the case.

R. King, BHRA Fluid Eng.: We at BHRA have studied the performance of jets and find that the stability (i.e. the distance downstream from the nozzle efflux to the point at which the jet breaks up) is critically dependent upon the upstream swirl and the mechanical difficulties encountered in the machining processes e.g. surface finish and ovality of the nozzle hole. Could these effects explain the lack of correlation between certain corrections of results?

Laufer: Upstream disturbances are expected to have a strong effect on the initial instability.

J. P. Sullivan, Purdue University: You mentioned that the initial shear layer seems to be controlling the frequencies but in the case of the stability of an isolated vortex ring the instabilities are really governed not only by the vortex core diameter but really the distribution of vorticity in the ring. Could you comment on this?

Laufer: I hope I made myself clear. The way I look at the problem, the initial shear instability only determines the frequency at which these vortices form and that is all. I don't understand the dynamics of what happens further downstream.

Sullivan: Also, in the case of the helical instability, have you tried to make any comparison of the mode structure of the helical vortices that you get there with Widnal's stability analysis?

Laufer: No, I have not.