Computer-Enhanced Analysis of a Jet in a Cross Stream

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Abstract

A DEMONSTRATION was made of the improvements obtained by computer enhancement of the analysis of near-field data from a jet in a cross stream. Isopleths of velocity, vorticity, and their components were produced on microfilm for sets of planes in three orthogonal directions. A comparison with a previous hand analysis of the same data showed the improvement and greater reliability achieved by the computer analysis in the determination of the jet boundaries, the jet centerline, and the centerlines of the bound vortices. A heretofore undetected stationary wave was revealed in the mixing region of the jet and cross stream. Displays of isopleths of the angle between the velocity and vorticity vectors demonstrated that Beltrami flow was approached in only the central region of the bound vortices.

Contents

Moussa et al.[1] analyzed wind tunnel data for the near field of a turbulent jet emerging from a pipe into a cross stream. They defined three essential features of the system: the jet centerline, the jet boundaries, and the bound vortex centerlines. They used hand-drawn isopleths in a data-rich set of planes perpendicular to the cross flow. Here we show the improvements achieved when the same data are used with computer enhancement and analysis in sets of planes in three orthogonal directions. Computer-drawn isopleths were produced on microfilm.

The Control Data 7600 computer at the National Center for Atmospheric Research was used to set up the three-dimensional velocity field on a grid of points at intervals of $D/8$, the smallest interval used in taking the original data (D is the outside diameter of the pipe). Interpolation and extrapolation were required to make the new data base suitable for computer analysis. The reliability of this expansion of the data base was assessed in several ways: 1) for the same planes, the present results and the results in Ref. 1 were in agreement; 2) features covering intervals of $D/4$ were successfully interpreted in Ref. 1, and no features smaller than this were considered here; 3) patterns in planes orthogonal to those used in Ref. 1 were found to be as smooth as those in the planes they used; 4) some evidence for a new feature revealed here, a wave in the mixing region of the jet and cross stream, can be found in the plots of Ref. 1; and 5) Moussa and Eskinazi[2] confirmed the reliability of the five-hole pressure probe, used to obtain the direction of the velocity vector, through a comparison with results obtained with an inclined hot wire.

Figure 1 shows the jet and the coordinate system. The "horseshoe" shapes indicate the locations of the crests of a stationary wave.[3] U_0 is the speed of the free cross stream, 8.5 m/s. The mean jet speed, as it enters the cross stream, is 29.6 m/s.

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Figure 2 shows the location of the jet centerline, defined by the velocity ridge in the velocity isopleths in the plane of symmetry, $Y/D=0$. The improvements through computer enhancement are shown by the larger number of points defining the centerline and by the points determined below $Z/D=1$, a region in which the centerline cannot be located in the planes used in Ref. 1. The bound vortex centerline, found here to lie in the plane $Y/D=0.5$, is shown in Fig. 2. A point on this line was defined in Ref. 1 as the point of maximum vorticity in a plane perpendicular to the cross stream. In the present analysis, this definition was extended to the other two sets of orthogonal planes. Disagreements with Ref. 1 were found for $X/D \leq 0.25$, an ambiguous region for the planes used in Ref. 1. Figure 3 shows the clarity with which the bound vortex can be found in the X-Y planes in this region and elsewhere. The jet boundary, also shown in Fig. 3, is the ridge of total vorticity. This definition is an extension of that used in Ref. 1 and formulated there for the Y-Z planes. Its use here, in all three orthogonal planes, gave a more reliable delineation of the jet boundary. Agreement among the various sets of planes was within one grid distance.

A stationary wave, not detected by the analysis in Ref. 1, was found in the turbulent mixing region of the jet and cross stream. This wave and the locations of the crests A, B, and C are shown in Fig. 4 for the velocity field in the plane of symmetry, $Y=0$. (The same crests are also shown in Fig. 1.) In other planes, the velocity field did not clearly define the wave, but evidence for it was seen most clearly in components of vorticity, especially the Z component Ω_z. Figure 5 shows the evidence for the wave in the positive and negative cells of Ω_z, where A-D are the cell centers of the wave crests and define a cell centerline. The "horseshoe" shapes in Fig. 1 are a schematic representation of these cells and their centerlines.

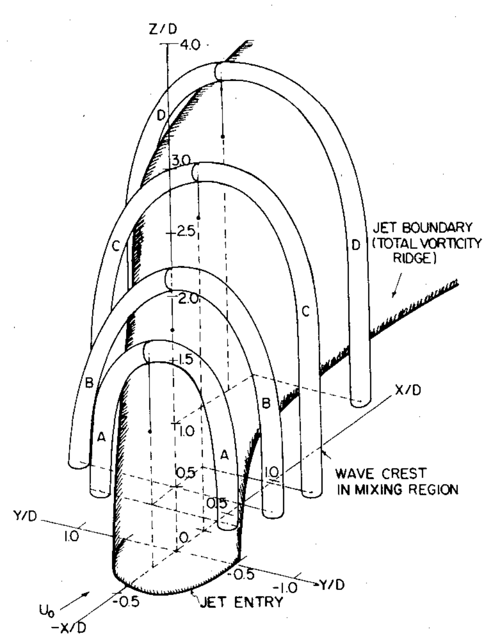

Fig. 1 Coordinates and jet with vorticity cells at wave crests A-D.

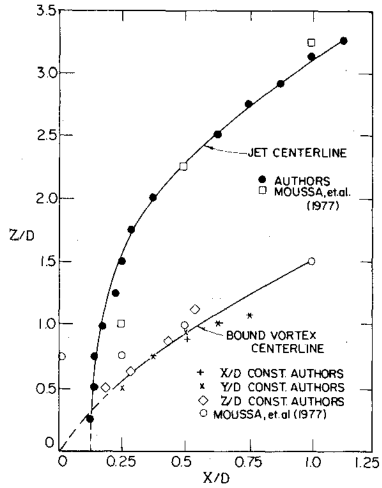

Fig. 2 Jet centerline and bound vortex centerline.

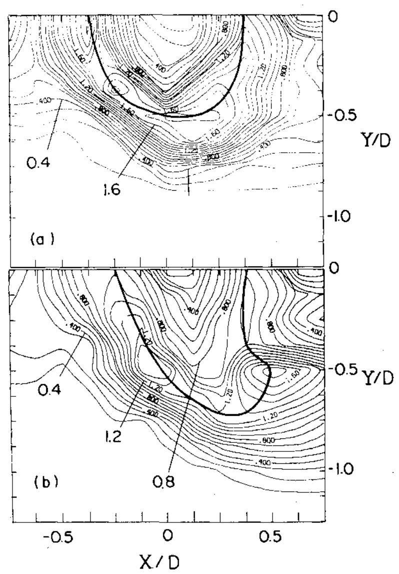

Fig. 3 Total vorticity isopleths in planes of constant Z/D: a) $Z/D=0.5$, interval 0.1; b) $Z/D=1.0$, interval 0.1.

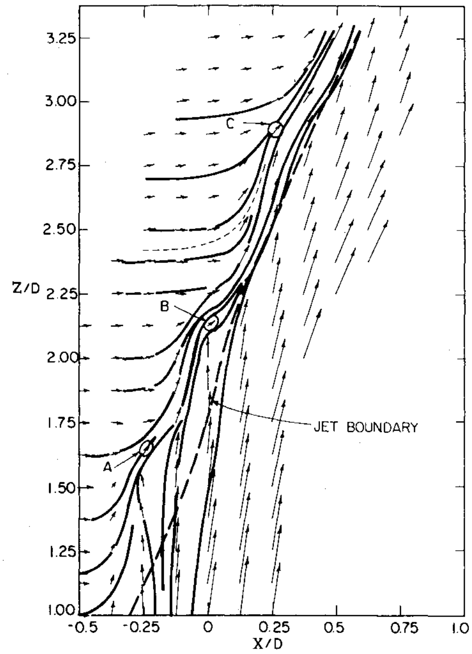

Fig. 4 Velocity field with streamlines in the plane of symmetry, $Y/D=0.0$ (A-D are points on the wave crest centerlines).

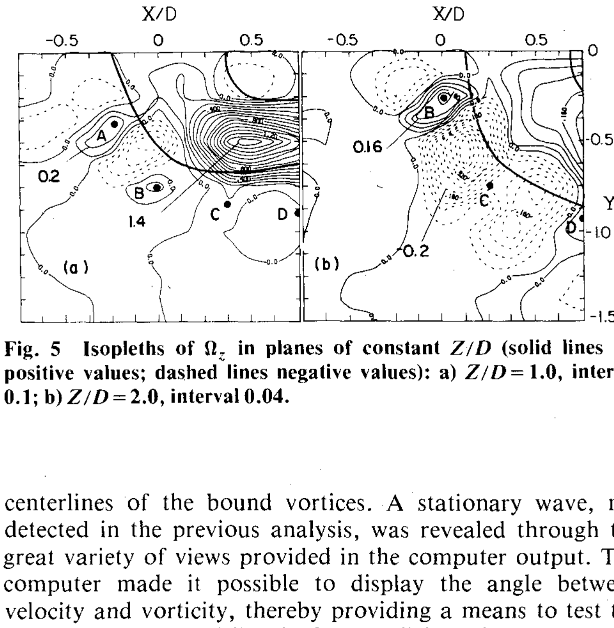

Fig. 5 Isopleths of Ω_z in planes of constant Z/D (solid lines are positive values; dashed lines negative values): a) $Z/D=1.0$, interval 0.1; b) $Z/D=2.0$, interval 0.04.

The stationary wave is qualitatively explained as a standing wave moving as a whole with the mean motion of the fluid in the mixing region of the jet and the cross stream. The two traveling waves, one moving downstream, the other upstream, have speeds relative to the fluid equal to that of the mean speed of the fluid. Hence, the upstream wave is stationary with respect to laboratory coordinates, whereas the downstream wave is oscillatory relative to laboratory coordinates and has no average effect on the measuring instruments. One possible cause of the reflections required to produce a standing wave is the asymmetry produced by the curvature in the flow.

It is predicted in Ref. 1 that the flow of the jet in a cross stream will eventually become Beltrami flow, for which the velocity and vorticity vectors are either parallel or antiparallel. The computer-calculated isopleths for this angle, in the X-Y planes, clearly show that Beltrami flow is approached only near the centerline of the bound vortex.

It is concluded that a computer-enhanced analysis of the data reported in Ref. 1 not only gives reliable results but, through the diversity of plots made readily possible by this method, provides unambiguous and more accurate means for determining the jet boundaries, the jet centerline, and the centerlines of the bound vortices. A stationary wave, not detected in the previous analysis, was revealed through the great variety of views provided in the computer output. The computer made it possible to display the angle between velocity and vorticity, thereby providing a means to test the approach to Beltrami flow in the near-field region.

Acknowledgments

The authors thank Z. Moussa for the use of his data and S. Eskinazi for valuable suggestions. This work would not have been possible without the support and encouragement of E. Danielsen. For the use of the computer, acknowledgment is made to the National Center for Atmospheric Research, which is sponsored by the National Science Foundation.

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