THE FORMATION OF ELLIPTIC WAKES

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LIST OF FIGURES

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Abstract

The wakes formed behind sharp-edged, bluff, elliptical bodies are not aligned with the body. That is, the major axis of the wake is aligned with the minor axis of the body. This effect was observed in both the mean velocity and the turbulent intensity in the wake several body diameters downstream of the body. The turbulent energy in the wake flow near the body displayed a periodicity which was correlated using a Strouhal number. Over the Reynolds number range from 8×10^3 to 7×10^4, the Strouhal number depended only on the body eccentricity.

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* Refers to references at the end of the paper.

Introduction

An experimental study of turbulent, elliptic wakes offers several advantages which are not found in the axisymmetric or two-dimensional cases to test eddy diffusivity approximations. The present work was undertaken to provide experimental data for comparison with previously published theoretical predictions of Steiger and Bloom (1963) and the authors (1964). A complete description of this research is available in the dissertation of Kuo (1965). However, this note summarizes an unexpected, fascinating observation that elliptical wakes formed behind sharp-edged, bluff, elliptical bodies are rotated 90 degrees. The major axis of the wake several body diameters downstream of the body is aligned with the minor axis of the body. This discovery was "unexpected" because it had previously not been predicted theoretically nor observed experimentally (e.g. see the reviews of Rosenhead (1953), Marris (1964) or Hallen (1964)).

Experimental Arrangement

The experiments were conducted in a low-speed wind tunnel located in the Fluid Dynamics and Diffusion Laboratory. The tunnel is a recirculating type and has a test section 6 ft. x 6 ft. in cross section and 30 ft. long. An inlet contraction ratio of 4 to 1 with damping screens yields a free stream turbulence level of less than 2 percent.

The mean velocity U_∞ in undisturbed flow was set at three values (58.3, 29.8 and 19.6 fps) in the course of the experiments.

Figure 1 is a sketch showing the disks mounted in the inlet of the test section of the wind tunnel. This sketch also defines the coordinates for the wake survey and depicts the orientation of the mean velocity wake.

Table 1 lists the dimensions of the disks which were used to generate the wakes. One set had an equivalent frontal area of a 1-inch circular disk, while the other set had the area of a 3-inch circular disk. Each set contained a circular disk and two elliptical disks having eccentricities ϵ (ratio of minor to major axis) of 0.6 and 0.2. The disks were made of clear plastic and had a sharp edge on the upstream face.

The mean velocity was calculated from pitot tube data. A constant-temperature, hot-wire anemometer was used to sense the axial turbulent fluctuations in velocity. The spectral analysis of the anemometer signal was performed using two analog circuits: a constant-percentage band-pass analyzer (Bruel and Kjaer Type 2109) and a constant band-pass ($\pm$ 1 cps) analyzer (Technical Products Spectrum Analyzer TP626, 627, 633).

Results and Discussion

The configuration of the elliptic wake is illustrated in typical mean velocity profiles shown in figure 2. The radii of the disks which formed the wakes are shown as solid bars on the abscissa. The larger wake dimension is associated with the smaller body dimension. Similar data were obtained for 1 inch equivalent diameter disks having the same eccentricity range. For the data shown in figure 2, the Reynolds number based on free stream velocity U_∞ and equivalent body diameter D is 7.1×10^4.

Tests showed that the wake formation relative to the disk was unaffected by changes in the disk mounting system and in the angular orientation of the disk relative to the tunnel walls.

Hot-wire anemometer surveys showed that the turbulence intensity profiles of the wake were also rotated 90 degrees in a manner analogous to the mean velocity profiles. Typical profiles are shown in figure 3 where the radii of the disks which formed the wakes are shown as solid bars on the abscissa. The large wake dimension is associated with the smaller body dimension.

To study the formation of the wake in more detail, a single hot-wire anemometer was placed 1.5 ft. downstream of each disk. A survey was made with the anemometer which passed through the center-line of the wake on a path parallel to the minor axis of the disk. At the peak in the turbulent intensity profile, a power spectral analysis of the axial component of the turbulence was performed. Sample spectra are shown in figure 4 for three mean velocities. Note the discrete peak in the turbulent energy at frequencies n_p which is a function of mean velocity. This peak is associated with the periodicity of the eddies shed by the disk. The periodicity in the flow was correlated using a Strouhal number based on the frequency of the peak turbulent energy, free stream velocity and equivalent body diameter. Figure 5 shows that over the Reynolds number range of this experiment, the Strouhal number depends only on the body eccentricity; $S = 0.145$ for the circular disks, $S = 0.168$ for $\epsilon = 0.6$ and $S = 0.237$ for $\epsilon = 0.2$. Extrapolation of this trend to an eccentricity of $\epsilon = 0$, which corresponds to a long flat plate, is not possible. For this case, Roshko (1955) found $S = 0.14$. The complexity of the wake formation is illustrated by the fact that there exists a second predominate shedding frequency associated with the small side of the disk. When a hot wire survey was made parallel to the major axis of the elliptic disk and a power spectral density analysis made of the peak signal at the same axial station ($x = 1.5$ ft), a peak turbulent energy was observed which correlated with a $S = 0.124$ for the $\epsilon = 0.2$ disk.

Flow Visualization

Figures 6 and 7 are some preliminary photographs taken of the disks in an open channel flow of water at 0.15 fps. Hydrogen bubbles generated on an upstream wire as described by Schraub et al. (1965) make the wake visible. It will be necessary to take synchronous moving pictures from the vertical and horizontal planes in order to draw definite conclusions concerning the wake formation. However, present photographs show that the dominant vorticity is generated along the long axis of the elliptic disk in what appears to be alternately shedding vortices. Figure 6a suggests that a small tip vortex might be shedding from the outer tip of the major axis. The hot-wire anemometer results indicate that this small tip vortex sheds at a different frequency than the long vortex.

Although certain aspects of the formation of wakes behind elliptic disks have been discussed here, we have avoided presenting hypothesis of "why" the wake is not simply aligned behind the bluff body. It is not difficult to speculate, but it seems prudent to study the base pressure and a more complete set of movie visualizations before proposing a model.

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References

1. STEIGER, M. H. and BLOOM, M.H. 1963. Three-dimensional Effects in Viscous Wakes. AIAA Journal, 1, 776-782.

2. KUO, Y.H. and BALDWIN, L.V. 1964. Comments on Three-Dimensional Effects in Viscous Wakes. AIAA Journal, 2, 1163-64.

3. KUO, Y. H. 1965. Three Dimensional Turbulent Wake. A dissertation presented in partial fulfillment of requirements for the degree Doctor of Philosophy at Colorado State University.

4. ROSENHEAD, L. 1953. Vortex Systems in Wakes. Advances Applied Mechanics, Vol. III, Academic Press, Inc., p. 185.

5. MARRIS, A. W. 1964. A Review on Vortex Streets, Periodic Wakes and Induced Vibration Phenomena. Trans. ASME Ser. D, J. Basic Eng., 185-196.

6. HALLEN, R. M. 1964. A Literature Review on Subsonic Free Turbulent Shear Flow. Stanford University Report MD11 (AFOSR - TN-5444).

7. ROSHKO, A. 1955. On the Wake and Drag of Bluff Bodies. J. Aero. Sci., 22, 124-132.

8. SCHRAUB, F. A., KLINE, S.J., HENRY, J., RUNSTADLER, T.W., JR., and LITTELL, A. 1964. Use of Hydrogen Bubbles for Quantitative Determination of Time Dependent Velocity Fields in Low Speed Water Flow. Stanford University Report MD10, (AFOSR Contract AF49(638) - 1278).

Table 1, Dimensions of disks

Body Eccentricity	Equivalent Diameter of Disk	Major Axis, inches	Minor Axis, inches	Thickness of disks, inches
1.0	3 inch	3.00	3.00	0.50
	1 inch	1.00	1.00	0.25
0.6	3 inch equivalent	3.88	2.32	0.50
	1 inch equivalent	1.29	0.775	0.25
0.2	3 inch equivalent	6.72	1.34	0.50
	1 inch equivalent	2.24	0.448	0.25

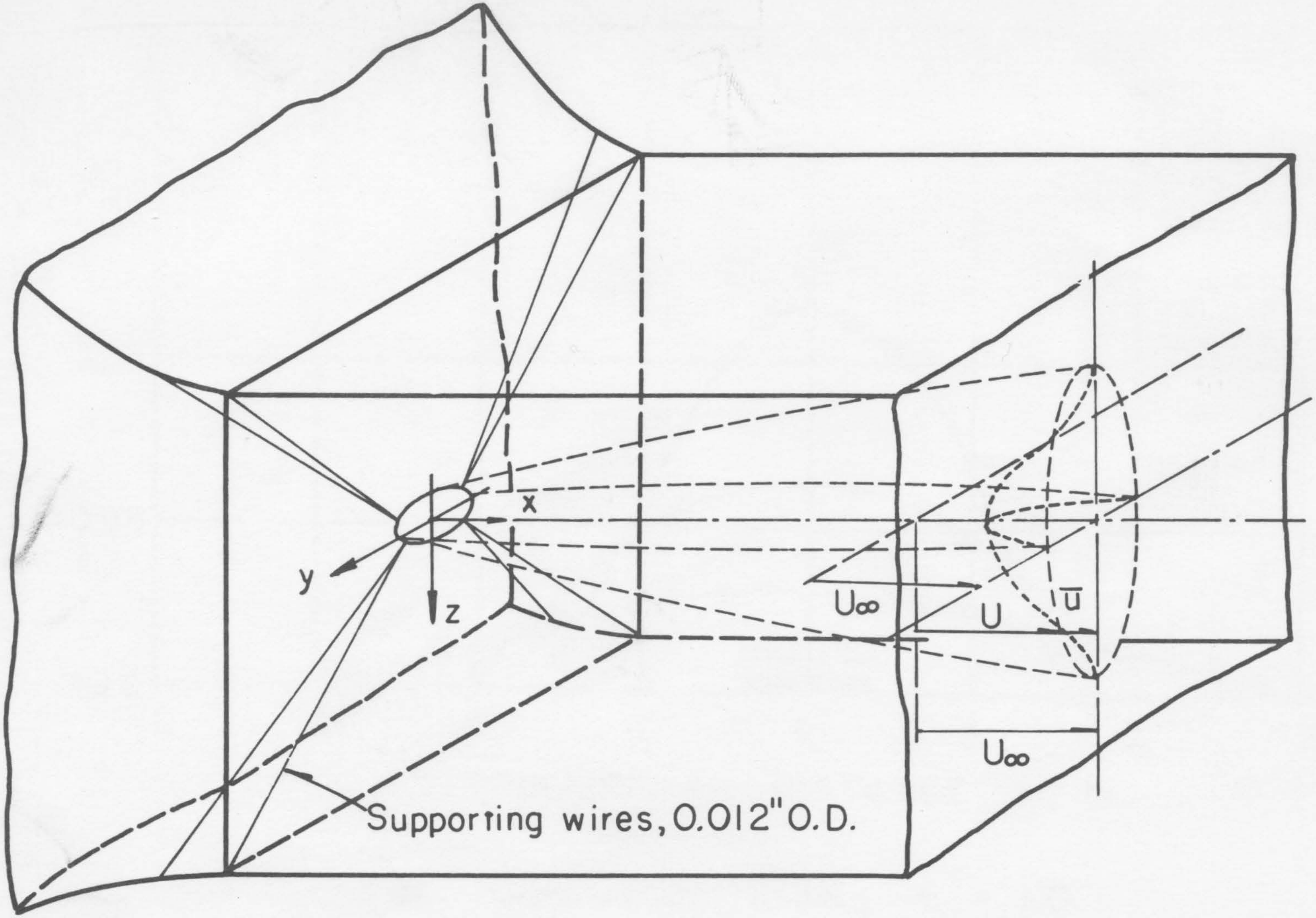
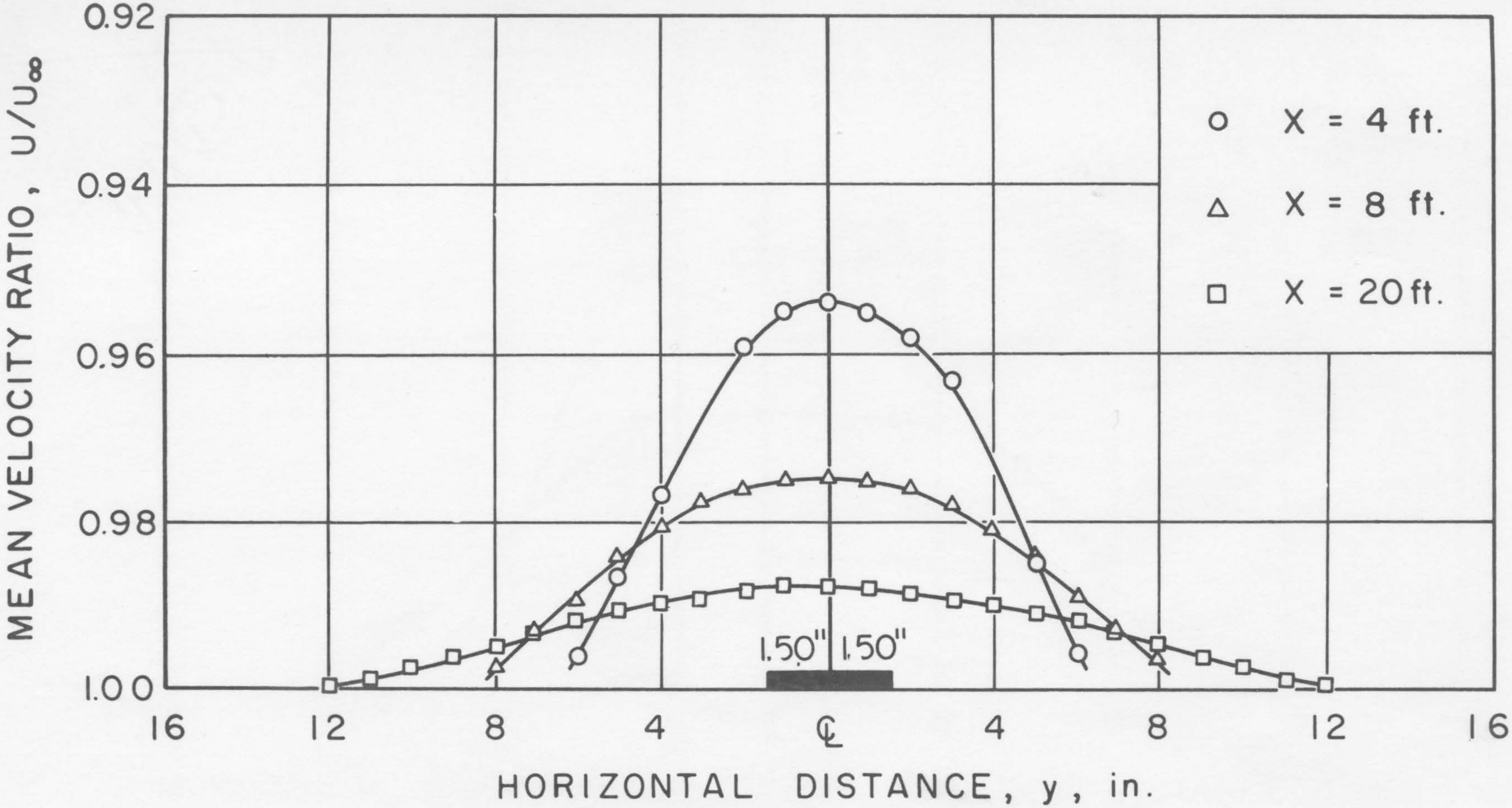


Figure 1. Sketch showing position of the disk in the wind tunnel.



(a) CIRCULAR DISK, $\epsilon = 1.0$

Figure 2. Velocity profiles at various axial stations behind disks having 3 inch equivalent diameter in ambient flow, $U_\infty = 58.3$ fps.

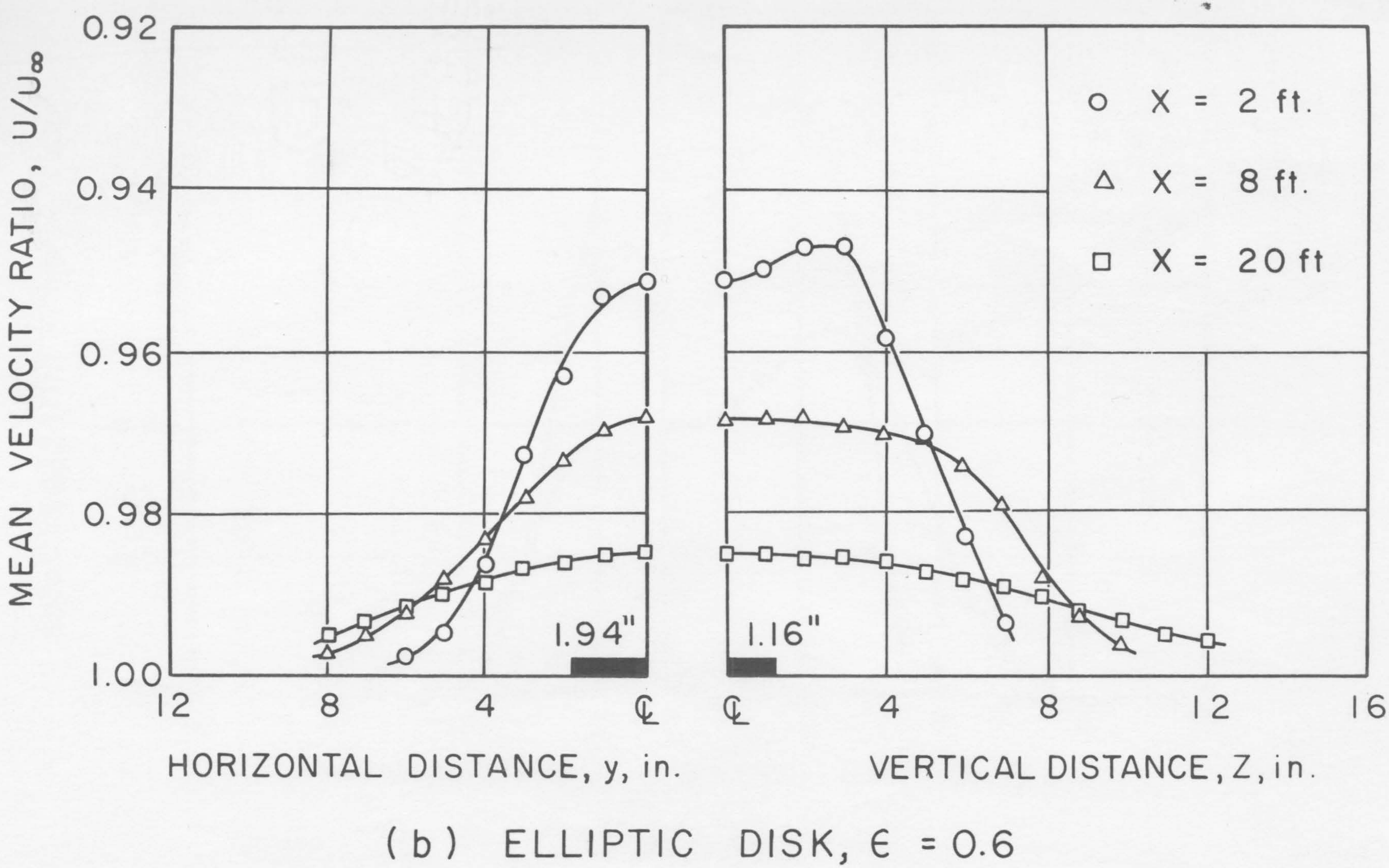


Figure 2. Velocity profiles at various axial stations behind disks having 3 inch equivalent diameter in ambient flow, U_∞ = 68.3 fps.

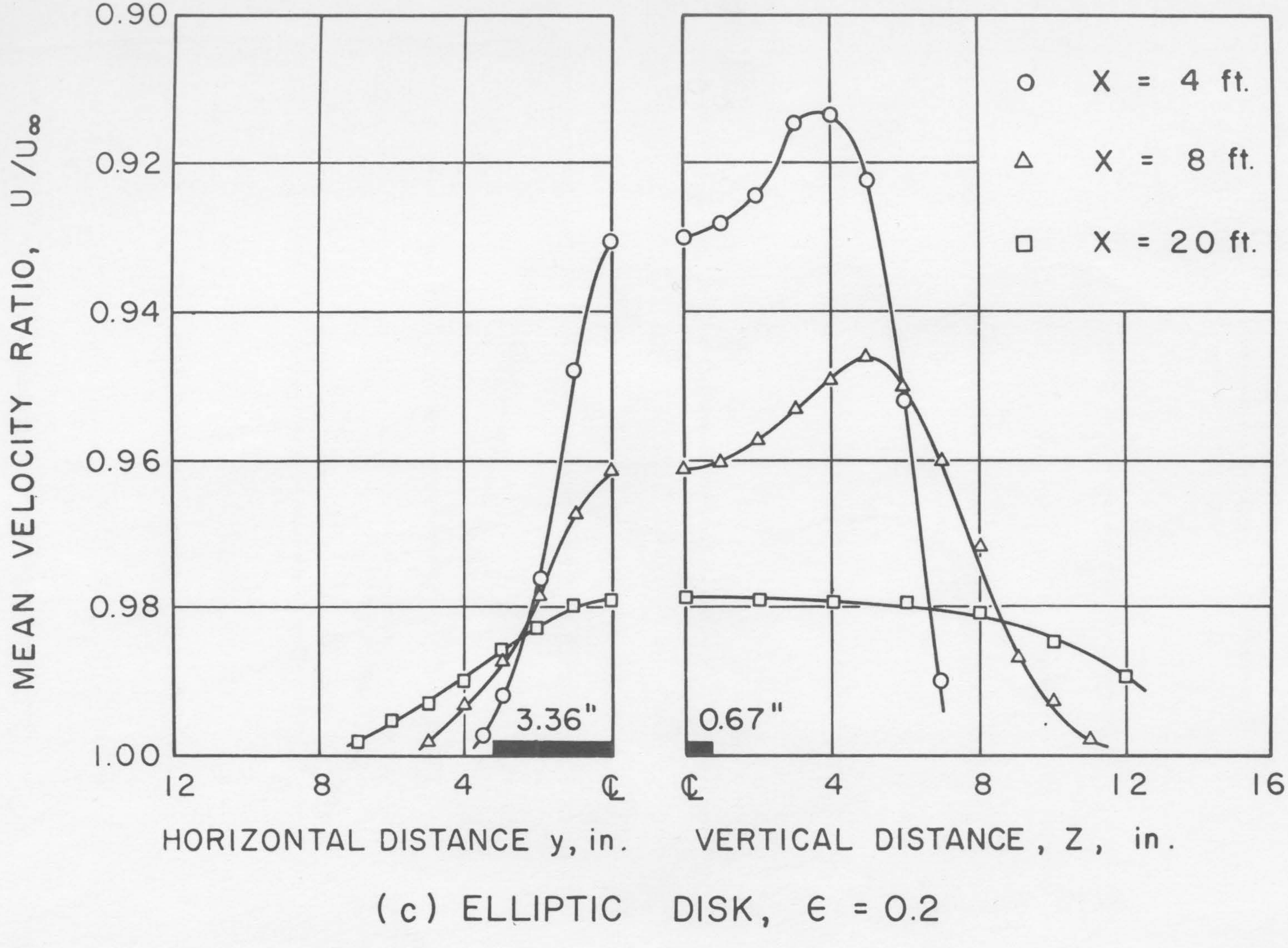
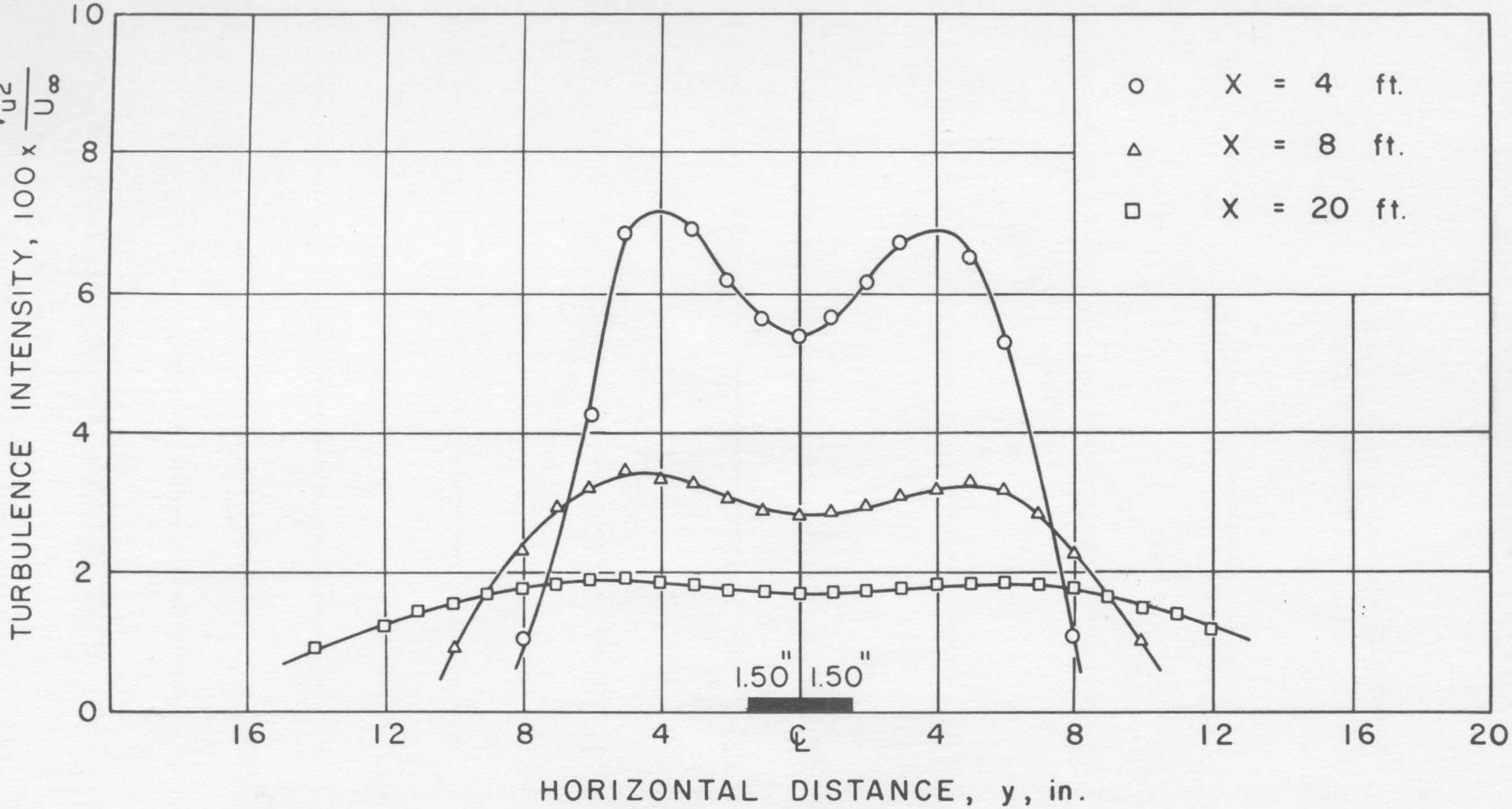


Figure 2. Velocity profiles at various axial stations behind disks having 3 inch equivalent diameter in ambient flow, U_∞ = 53.3 fps.



(a) 3 INCH DIAMETER, CIRCULAR DISK

Figure 3. Turbulence intensity profiles at various axial stations in ambient air flow, U_∞ = 58.3 fps.

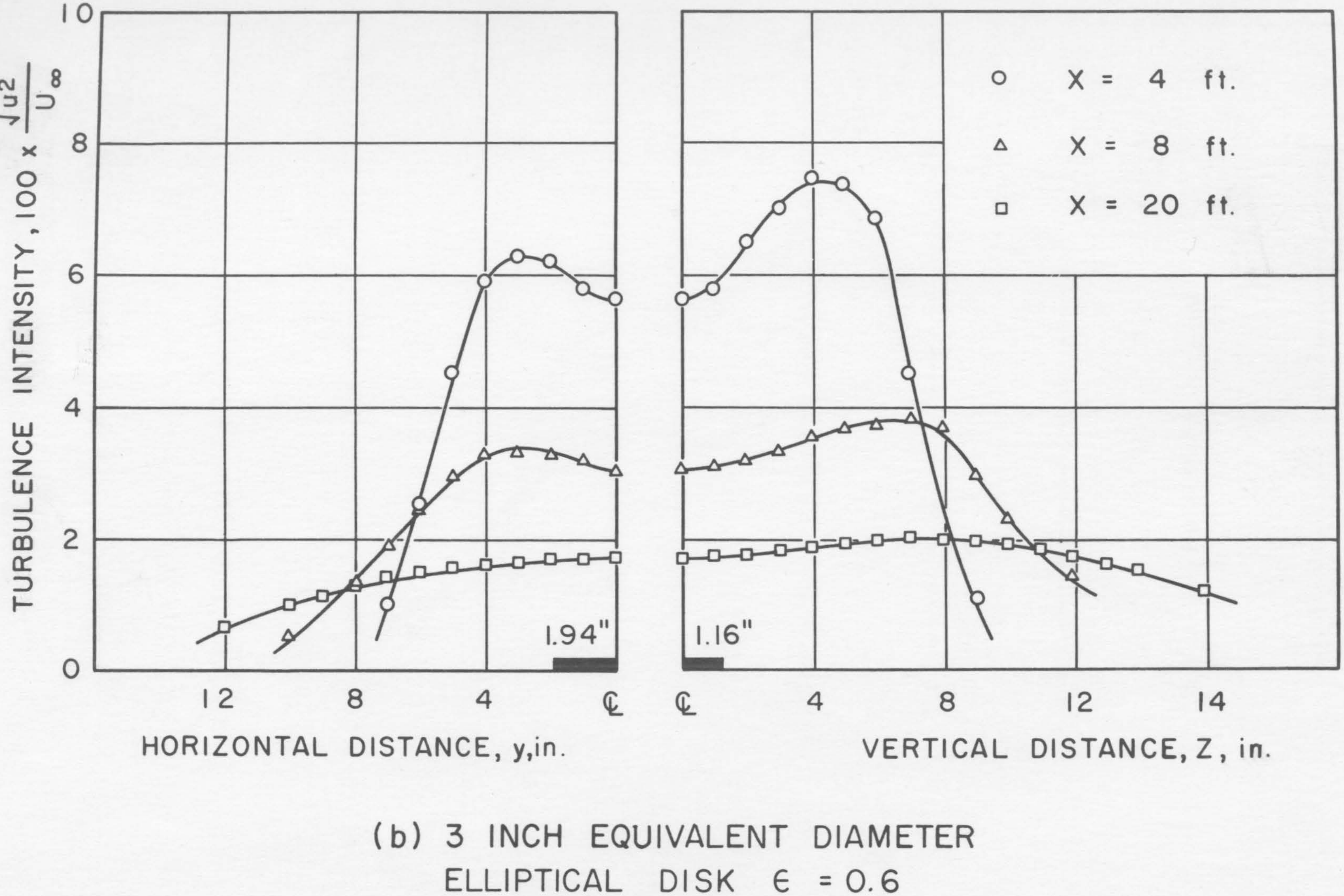


Figure 3. Turbulence intensity profiles at various axial stations in ambient air flow, $U_\infty = 58.3$ fps.

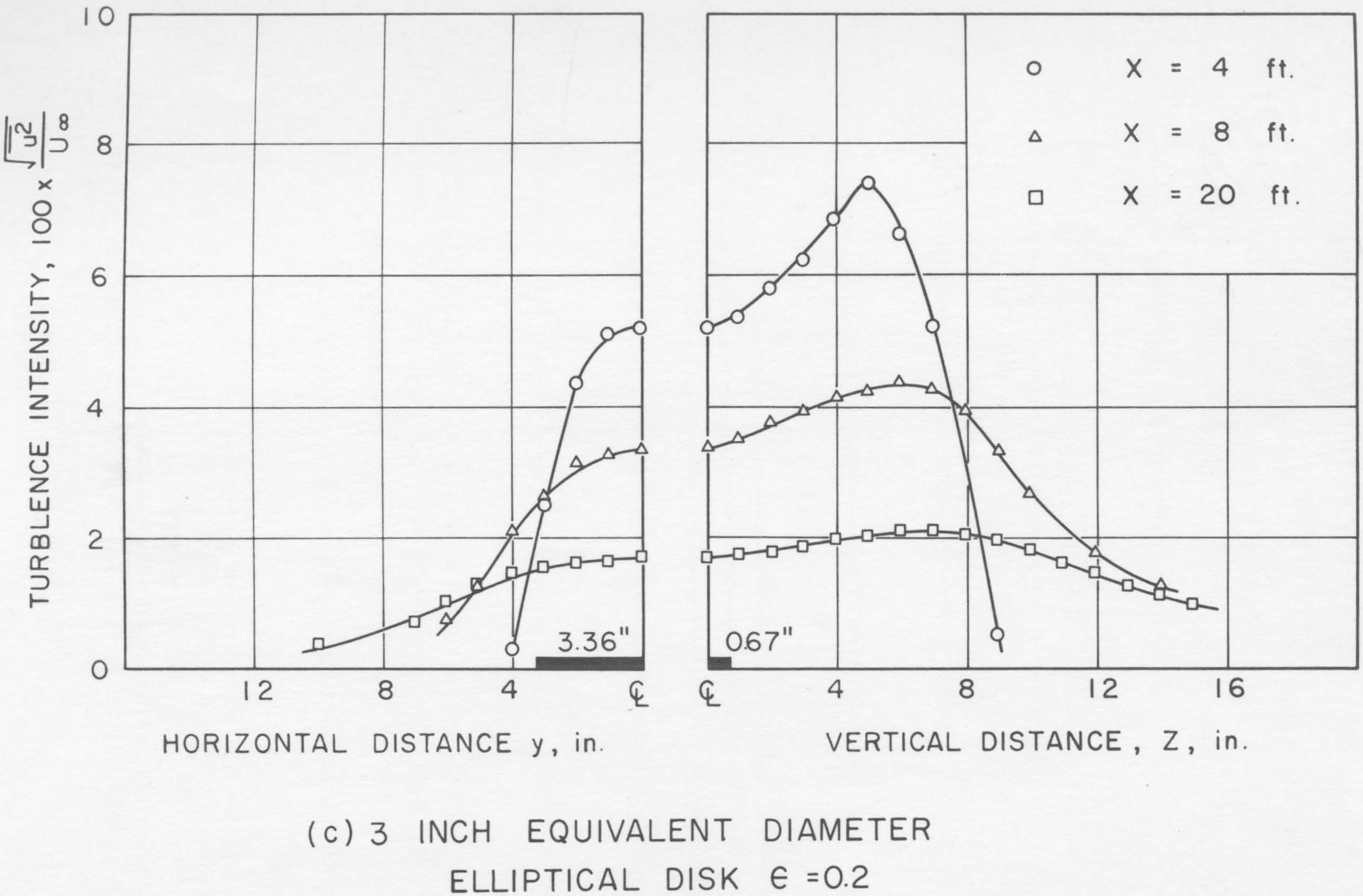


Figure 3. Turbulence intensity profiles at various axial stations in ambient air flow, U_∞ = 58.3 fps.

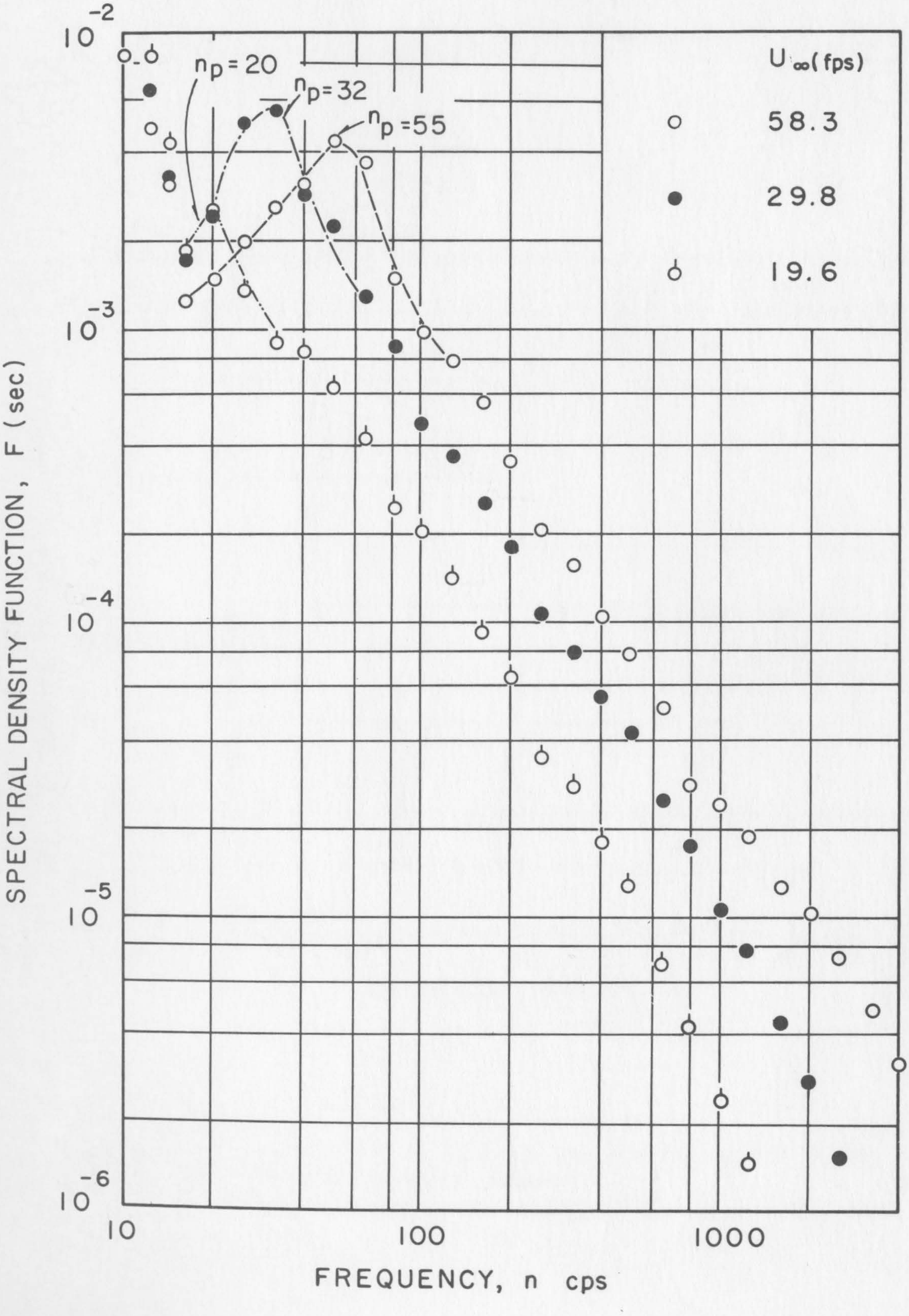


Figure 4. Power spectral density function for turbulence in wake of elliptic 3 inch diameter equivalent disk ($\epsilon = 0.2$, $\bar{x} = 1.5$ ft.)

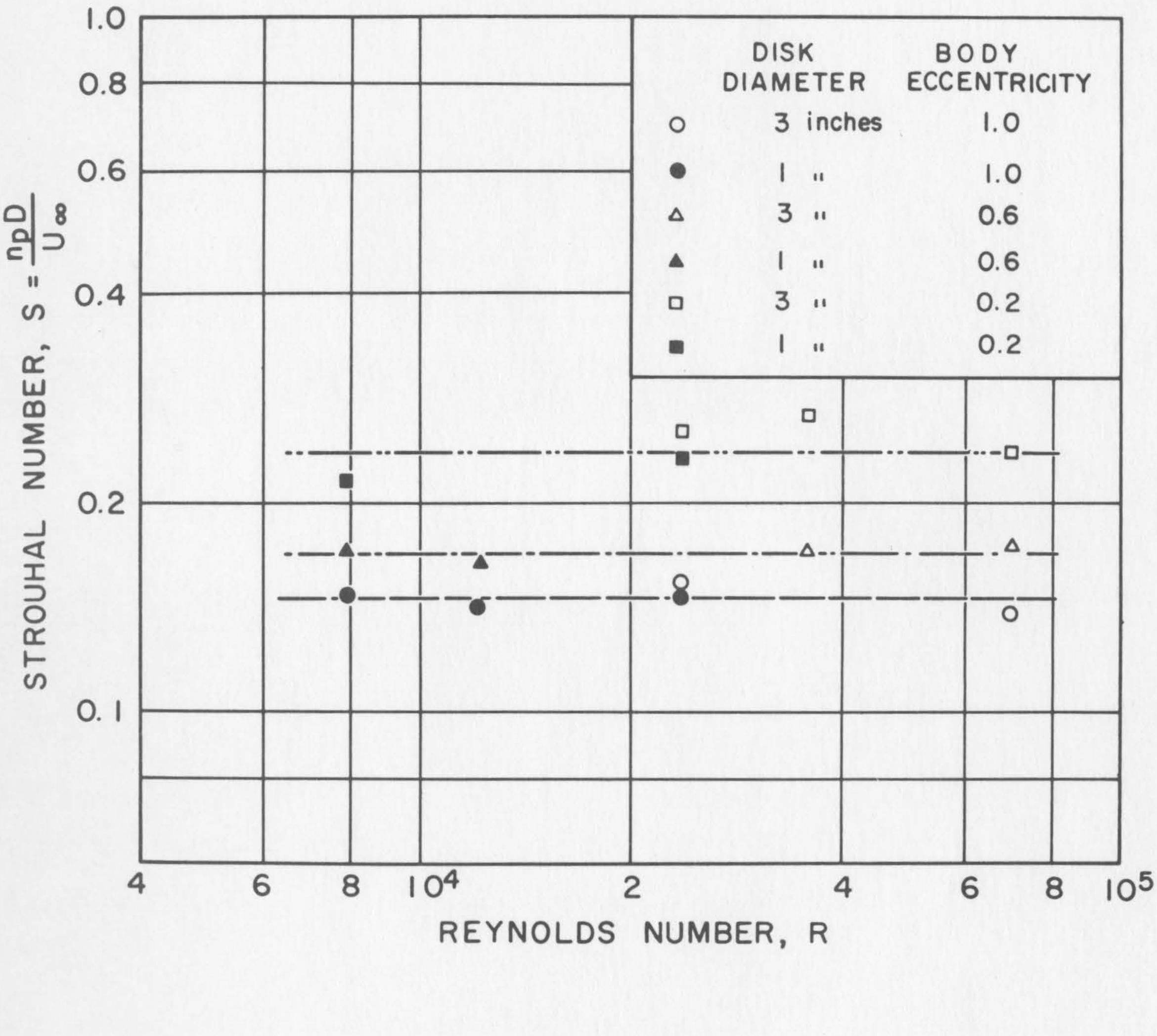
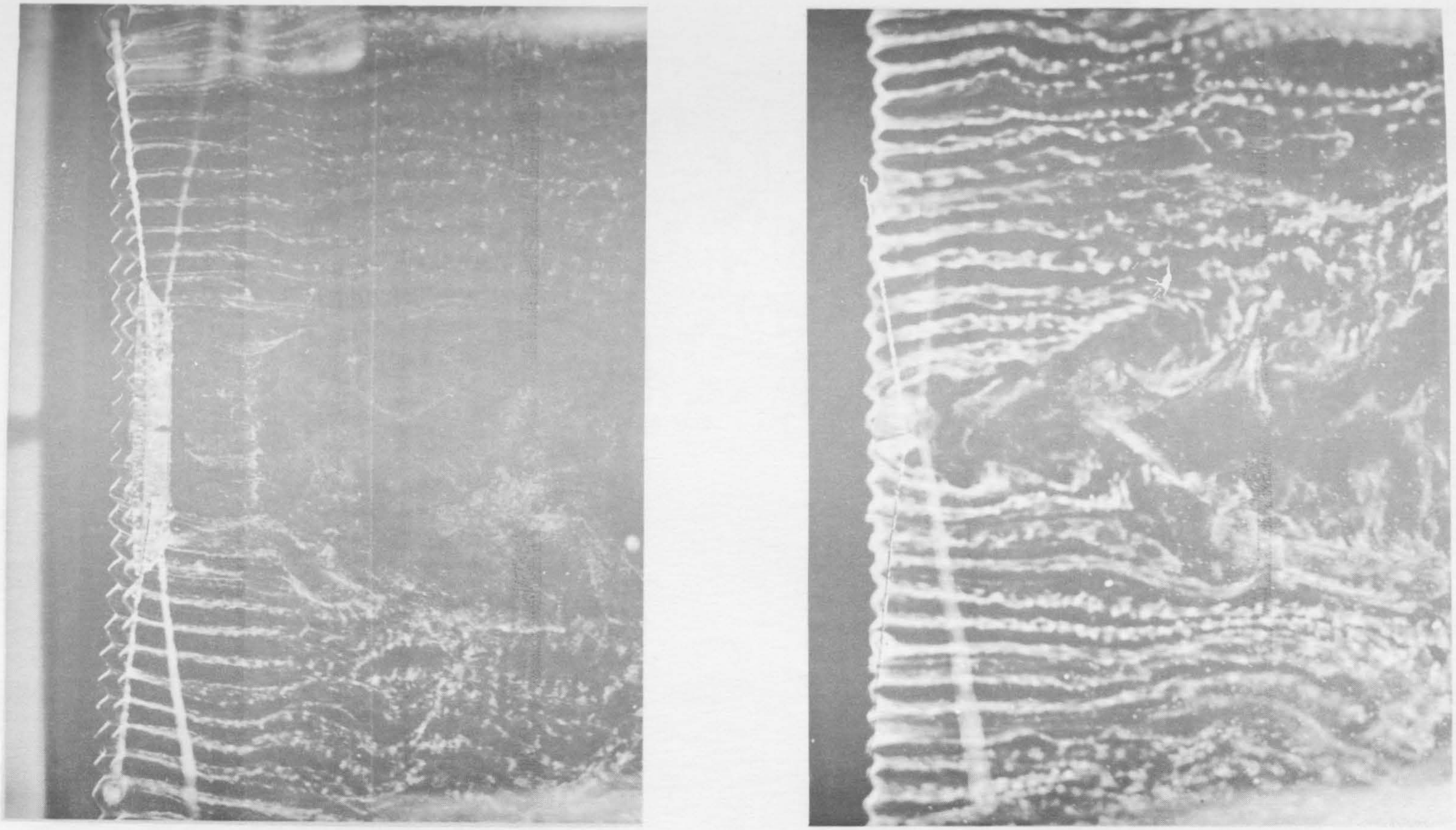


Figure 5. Correlation of Strouhal number data in the wake of bluff, elliptical bodies.



(a) (b)

Figure 6. (a) Development in the direction of major axis of the disk. (b) Development in the direction of minor axis of the disk.

Hydrogen-bubble visualizations showing behavior of the near wakes behind $\epsilon = 0.2$, 1 inch equivalent disk.

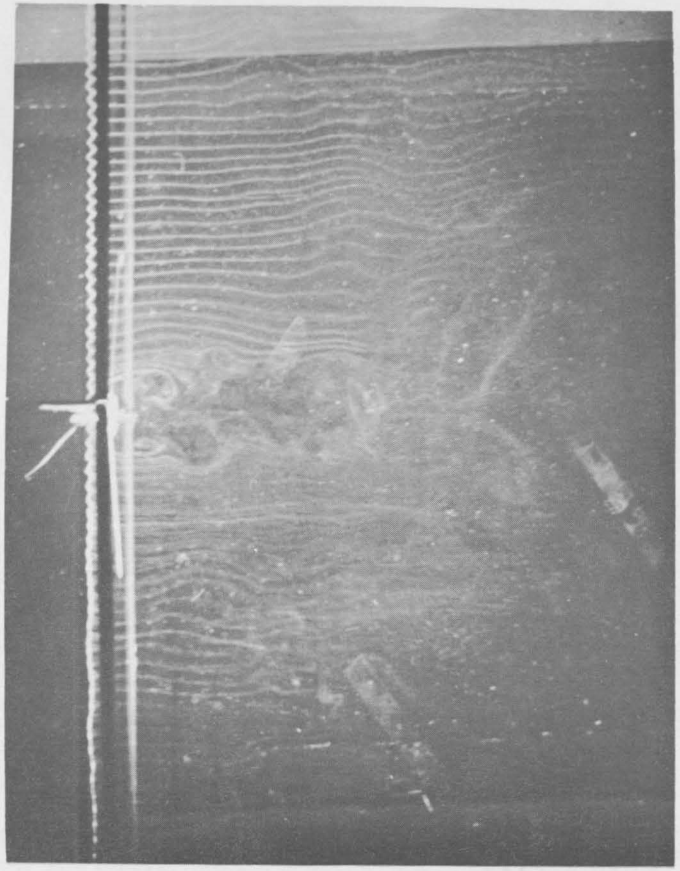


Figure 7. Hydrogen-bubble visualizations showing behavior of the near wake behind 1 inch circular disk.