LARGE-SCALE TURBULENT STRUCTURES IN JETS AND IN FLOWS OVER CAVITIES AND THEIR RELATIONSHIP TO ENTRAINMENT AND MIXING

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Introduction

Results of an experimental study are presented elucidating the presence of large-scale turbulent structures both in free jets and in axisymmetric flows over cavities. The purpose was to determine their role in entrainment, in mixing, in their growth, and in the production of noise. Although the flow configuration in the experiments was not that which exists in a thrust augmentor, the results nevertheless are of importance in understanding the various mixing and entrainment processes associated with the performance of such a device.

Recent realization of the presence of large-scale structures [(1-5)] in turbulent shear flows has generated an interst in advancing the understanding of their role in entrainment, mixing, production of noise and of the Reynolds stresses. In the present investigation the large-scale structures in jet flows were observed by simultaneous flow visualization and measurements of physical flow quantities to determine their development and their interaction with each other. Near field pressure signals as sensed by microphones were analyzed and matched with motion picture frames in an attempt to establish any link between the dynamics of these large-scale structures and the production of jet noise.

The experimental results on cavity shear layers were obtained under oscillating and non-oscillating flow conditions, i.e., with and without the presence of strong organized large-scale structures in the shear flow. Oscillations in flows over an axisymmetric cavity are caused by strong feedback from the downstream cavity corner [(6-7)]. They are accompanied by large-scale structures in the shear layer and can be altered by changing the cavity geometry or by changing the freestream flow conditions.

Results of Jet Flow Measurements

Subsonic jet flows were generated by expanding air at room temperature through a convergent nozzle which had an exit diameter of 4.2 cm. The jet discharged into an anechoic chamber. The Mach number M_e ranged between 0.1 and 0.9. The flow in the plenum chamber could also be modulated between 100 and 2000 Hz by first passing the flow through a pneumatic transducer, thereby exciting the jet flow. The rms velocity fluctuations at the center of the nozzle exit plane could be varied from 2% to as high as 8% of the mean jet velocity. These periodic flow fluctuations produced organized large-scale vortex structures in the jet shear layer. The interaction of these large-scale structures as they convected downstream and their role in the production of jet noise was investigated using the instrumentation system shown in Figure 1. Both still and high-speed Schlieren motion picutres up to 7000 frames/sec were taken. The duration of the flash used for the movies was 0.3 μs. The jet flow was made visible by mixing a small amount of CO_2 gas with the airflow in the plenum chamber. A series of microphones were placed in the near field and their output was synchronized with the high-speed motion picture frames so that near field pressure fluctuations could be analyzed simultaneously with the movies on a frame-by-frame basis.

A spark shadowgraph showing the large-scale sctructures in a non-excited jet flow at a nozzle exit Mach number M_e, of 0.69, and at a Reynolds number based on nozzle exit dia. $Re_D = 0.4 \times 10^6$ is shown in Figure 2. This shadowgraph clearly indicates the presence of large-scale structures as far as 5 to 7 jet dia. downstream of the nozzle exit. On close scrutinity of Figure 2 one can infer that the spacing between the structures approximately doubles as they propagate downstream. Because the merging of the large-scale structures occured many times at a relatively fast rate within a few jet diameters, it was not possible to relate the convection of these large-scale structures and their merging with each other to the near-field pressure signal. The process of merging of these structures was slowed down by exciting the jet flow, thereby introducing large-scale structures whose behavior could be studied visually and hence, merging identified.

A set of a sequential Schlieren motion-picture frames showing the behavior of artificially introduced large-scale structures is shown in Figure 3. The time duration between the frames was approximately 140 μs. The lower part of the mixing layer in frame 2 of Figure 3 shows a vortex structure which can be seen subsequently in frames 3, 4 and 5. In these frames the vortices that were shed earlier can also be seen. In frame 5, there are two vortices side by side which merged with each other sometime before frame 6 was taken. The merged structure then propagated downstream as can be seen in frames 7 and 8. From these high-speed motion picture observations, it was concluded that the time taken for the merging process of two artifically generated vortex structures to occur was about 10% of their life span in the jet flow. Under similar mean flow conditions in the nozzle an increase of 15 to 20% in the radial growth of the jet was observed when the jet was excited as compared to a jet that was not excited.

Figure 4 shows successive Schlieren motion picture frames along with a near-field pressure trace of microphone C, the location of which is shown above frame No. 1. Note the similarity of the behavior of the organized large-scale structures in Figure 4 as compared to those discussed in Figure 3. Observe that as a vortex structure passed below microphone C in frame 4 of Figure 4 there was no significant change in the near-field pressure signal. In frame 7, however, two adjacent organized structures interacted with each other, and instantaneously there was a rapid change in the pressure signal. This pressure pulse was then traced at later times by the other microphones located farther downstream in the near-field. From these measurements it was concluded that the near-field pressure signal of a jet is largely dependent on the dynamics of the interaction of large-scale structures in the jet. A more in-depth discussion on the relationship of large-scale structures and their generation of near-field pressure signals is given in Reference 8.

The influence of jet flow excitation on the distribution of the mean velocity along the jet centerline is shown in Figure 5. It is interesting to note the differences in these velocity distributions for cases in which the rms velocity fluctuations were random in nature with a magnitude of 2% as compared to periodic velocity fluctuations of nearly the same value at 2.3%. It can be seen in Figure 5 that the length of the potential core was reduced by almost half for the excited (pulsated) case as compared to the non-pulsated condition. One can infer from these results that the presence of large-scale structures produced by exciting the jet flow are greatly responsible for the rapid spread of the jet with greatly increased entrainment and mixing of the flow. Furthermore, increased excitation reduces the length of the potential core even more and also substantially reduces the mean velocity at the centerline at any given X/D beyond the potential core.

Flows Over External Axisymmetric Cavities

The experiments on flows over axisymmetric cavities were performed using a model which had an outside diameter d, of 2.0 in. as indicated in Figure 6. The model had an ellipsoidal nose with provision for variation of depth d, in steps together with a continuously adjustable width b. Either laminar or turbulent boundary layers could be obtained at the upstream edge of the cavity.

Flow over the cavity was visualized by injecting CO_2 gas at the base inside the cavity. Figure 7 shows a typical shadowgraph with width b = 0.4 in. and depth d = 0.5 in. Organized large-scale structures are observable over the cavity. For a Reynolds number, $Re_{\Theta_0} = 1.60 \times 10^3$ (where Θ_0 is the momentum tnickness at the upstream corner), and a depth $d/\Theta = 37.5$, the growth of the cavity shear layer is shown in Figure 8. Results are given both for a non-oscillating (with organized large-scale structures in the cavity shear layer) and for an oscillating shear layer over the cavity. The momentum thickness Θ, was determined by integrating the profiles of the mean velocity as determined by constant-temperature hot-wire anemometry. That is,

$$\Theta = \int_{-\infty}^{\infty} \frac{U}{U_\infty}\left(1 - \frac{U}{U_\infty}\right)dy \qquad (1)$$

In Eq. (1) y is the transverse coordinate, U is the local mean velocity and U_∞ is the freestream velocity. It is quite clear from Figure 8 that the growth rate $d\Theta/dx$, which indicates the entrainment rate, was approximately 0.021 for the non-oscillating shear layer. In the presence of organized large-scale structures for an oscillating flow over the cavity the value of $d\Theta/dx$ increased to as much as 0.046. This high entrainment rate of the shear layer seems to result from the presence of the organized large-scale structures shown in Figure 7.

Conclusions

From the experimental results of large-scale structures in jets and in flows over cavities, it can be concluded that the presence of these structures is greatly responsible for the growth of the shear layer, and for the entrainment. Furthermore, the near-field pressure signal in excited jet flows is caused primarily by the merging of adjacent large-scale structures. It is believed that both the entrained fluid as well as its eventual mixing with the jet flow can be controlled by introducing pulsation in the jet flow at a frequency for which the flow is most unstable.

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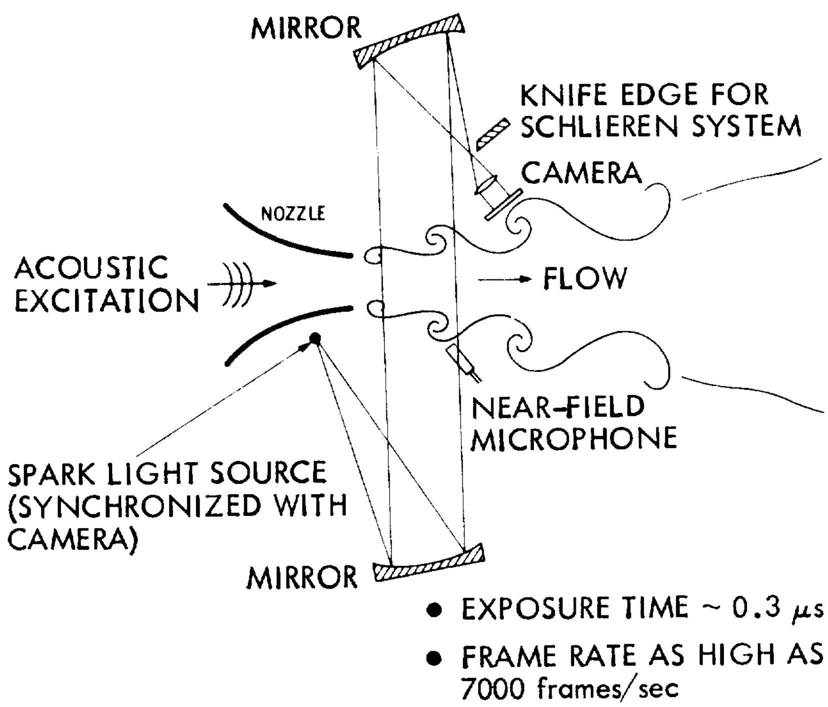


Figure 1. Schematic diagram indicating the experimental setup.

Figure 2. Shadowgraph showing large-scale turbulent structures.

$$M_{exit} \simeq 0.44$$

$$S \equiv fD/U_{exit} \simeq 0.14$$

DURATION IN BETWEEN FRAMES ≃ 120 μ/sec

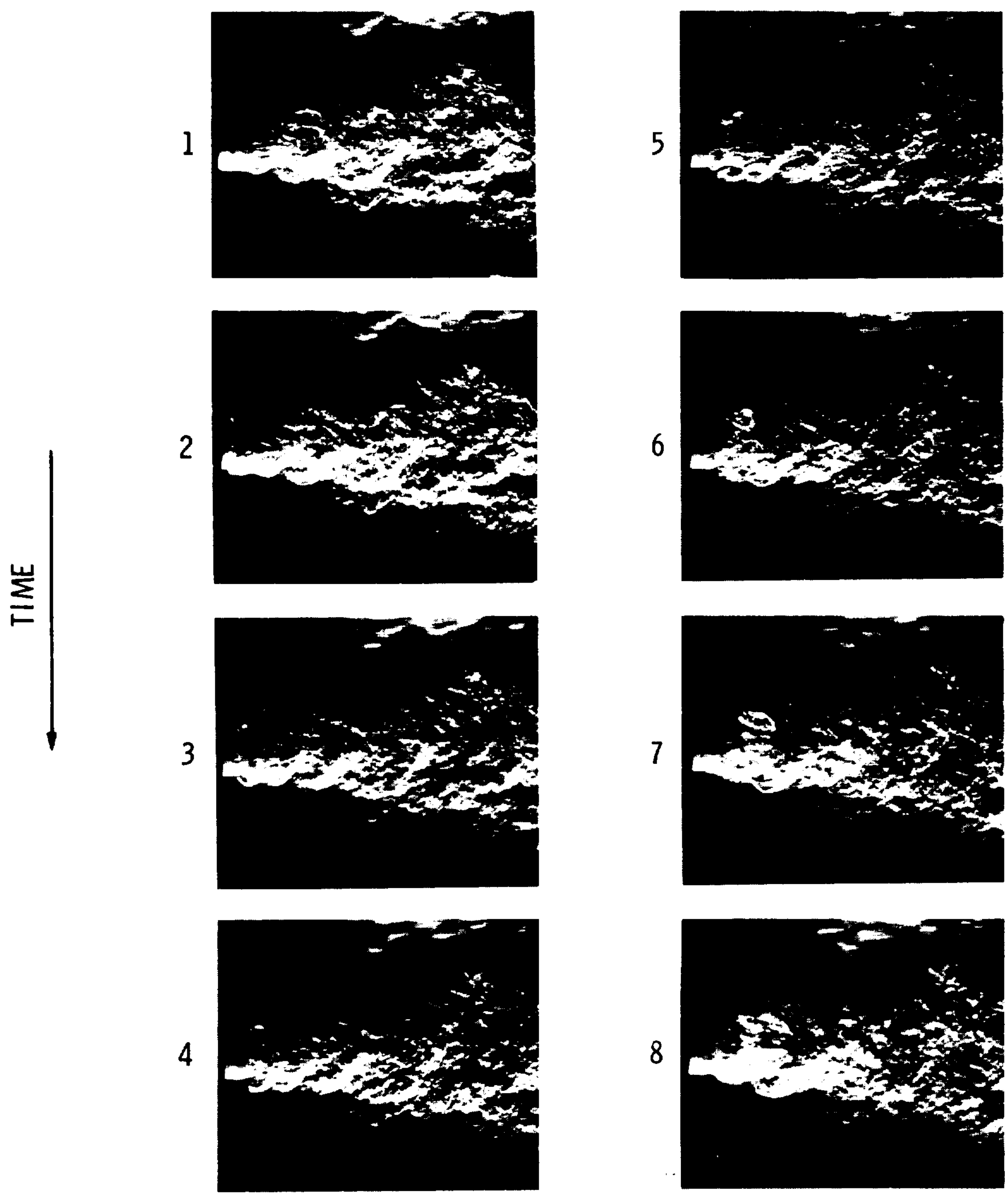


Figure 3. Large-scale coherent structures in excited jet flow.

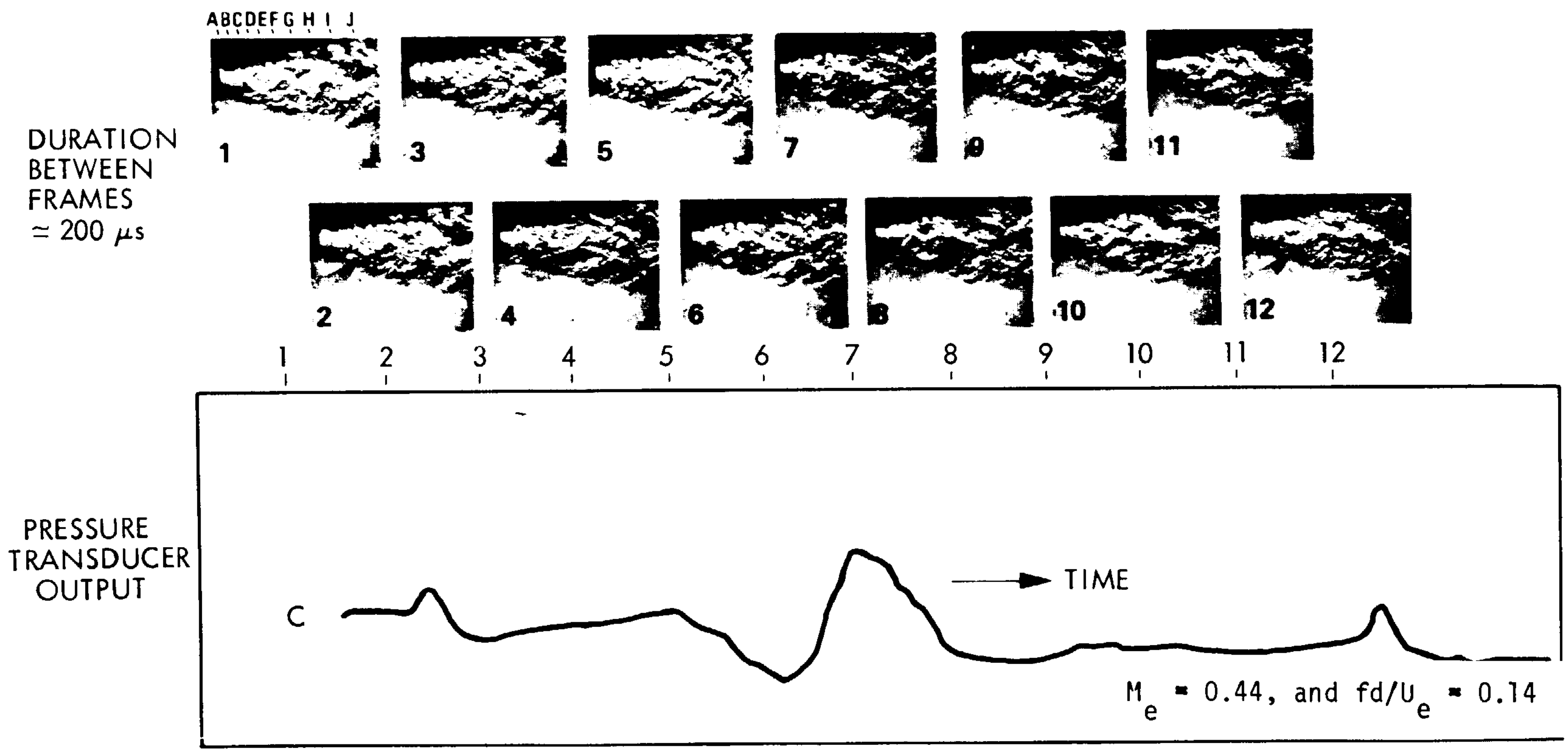


Figure 4. A sequence of high-speed Schlieren motion pictures of an excited jet along with a near-field pressure signal.

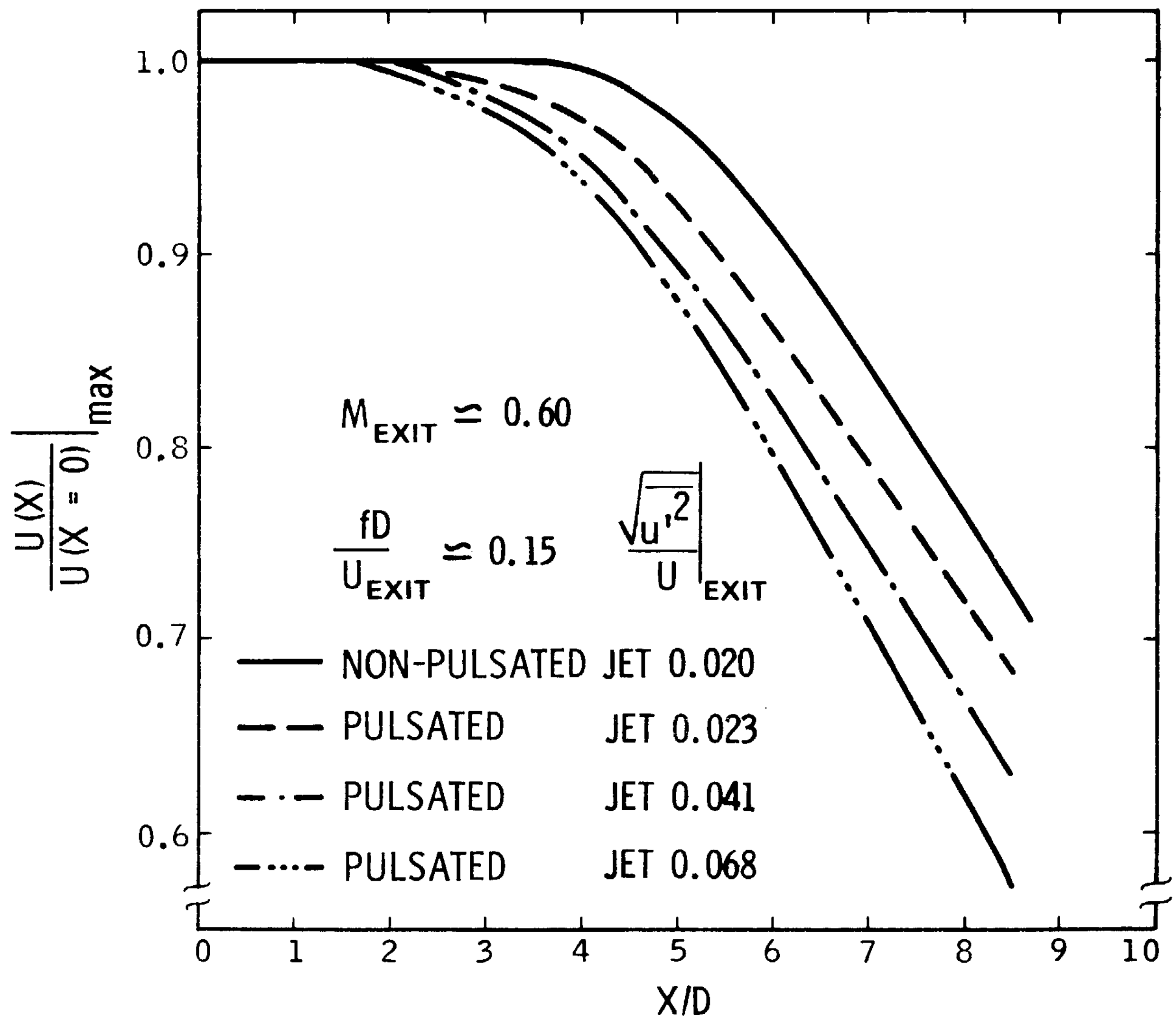


Figure 5. Influence of large-scale coherent structures on jet mixing.

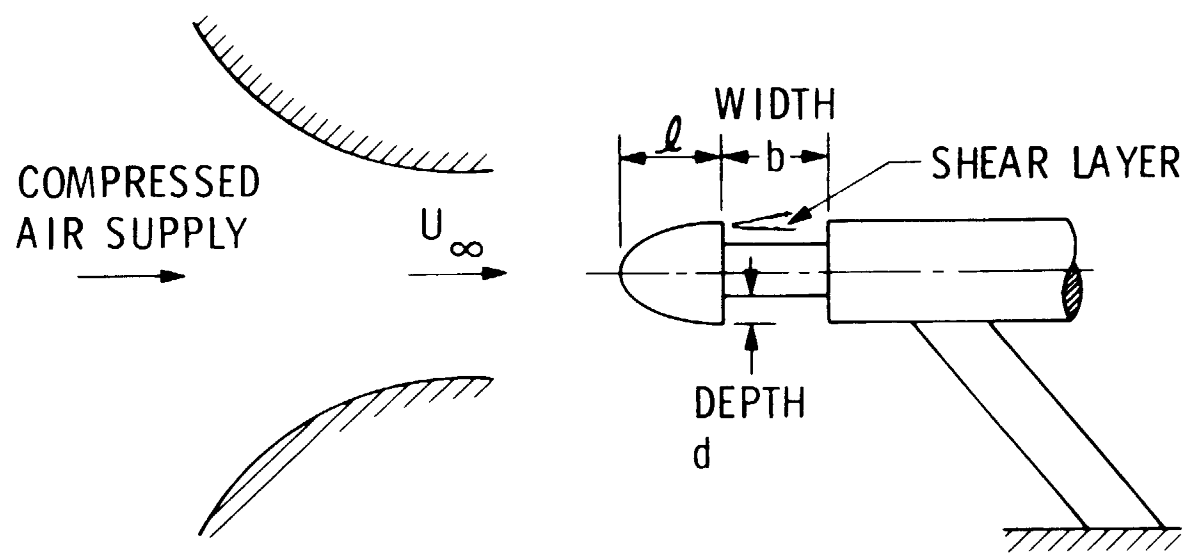
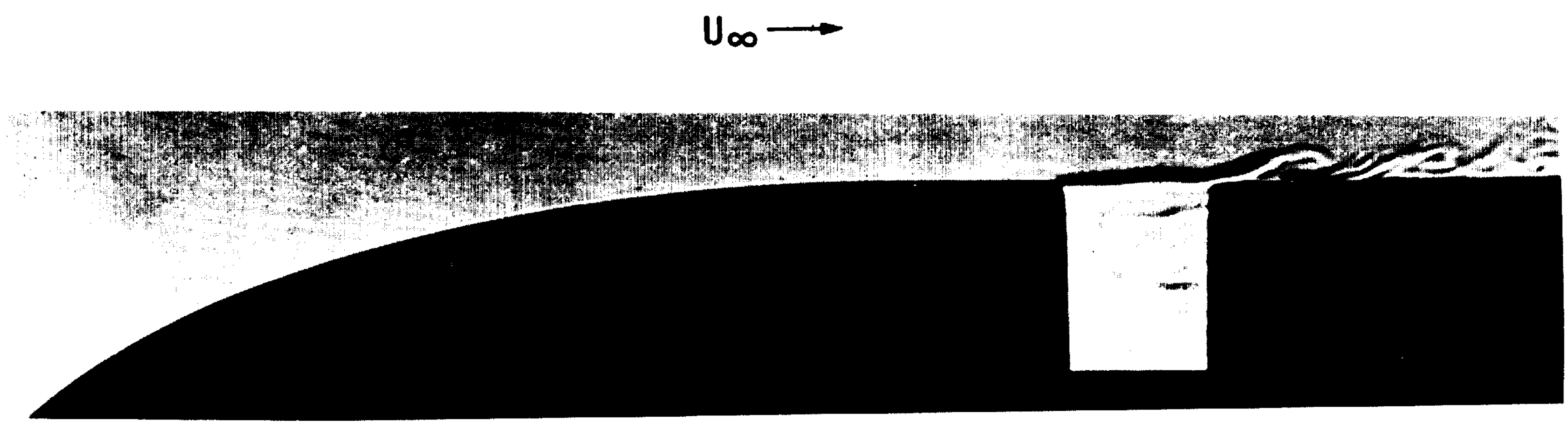
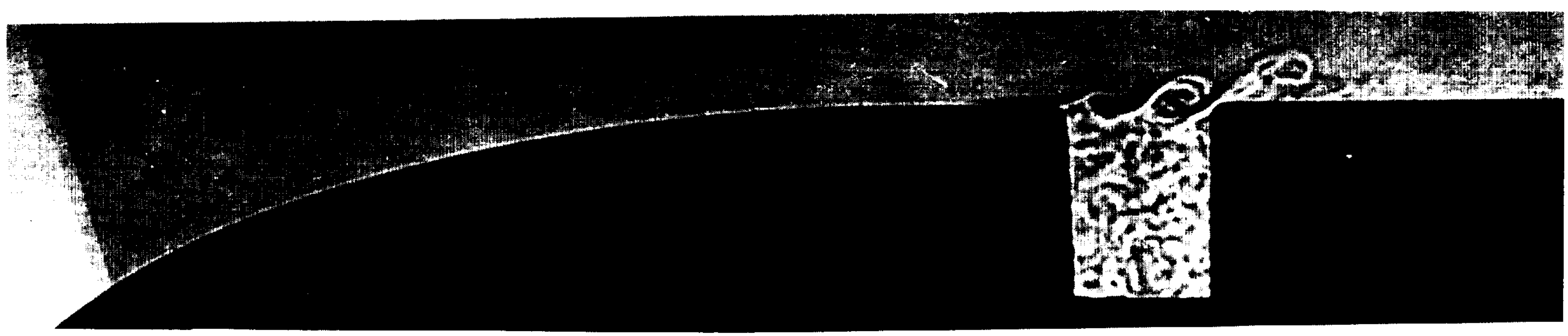


Figure 6. Sketch of axisymmetric cavity model.



(a) FREESTREAM VELOCITY U_∞ = 41 ft/sec



(b) FREESTREAM VELOCITY U_∞ = 96 ft/sec

Figure 7. Flow over a cavity.

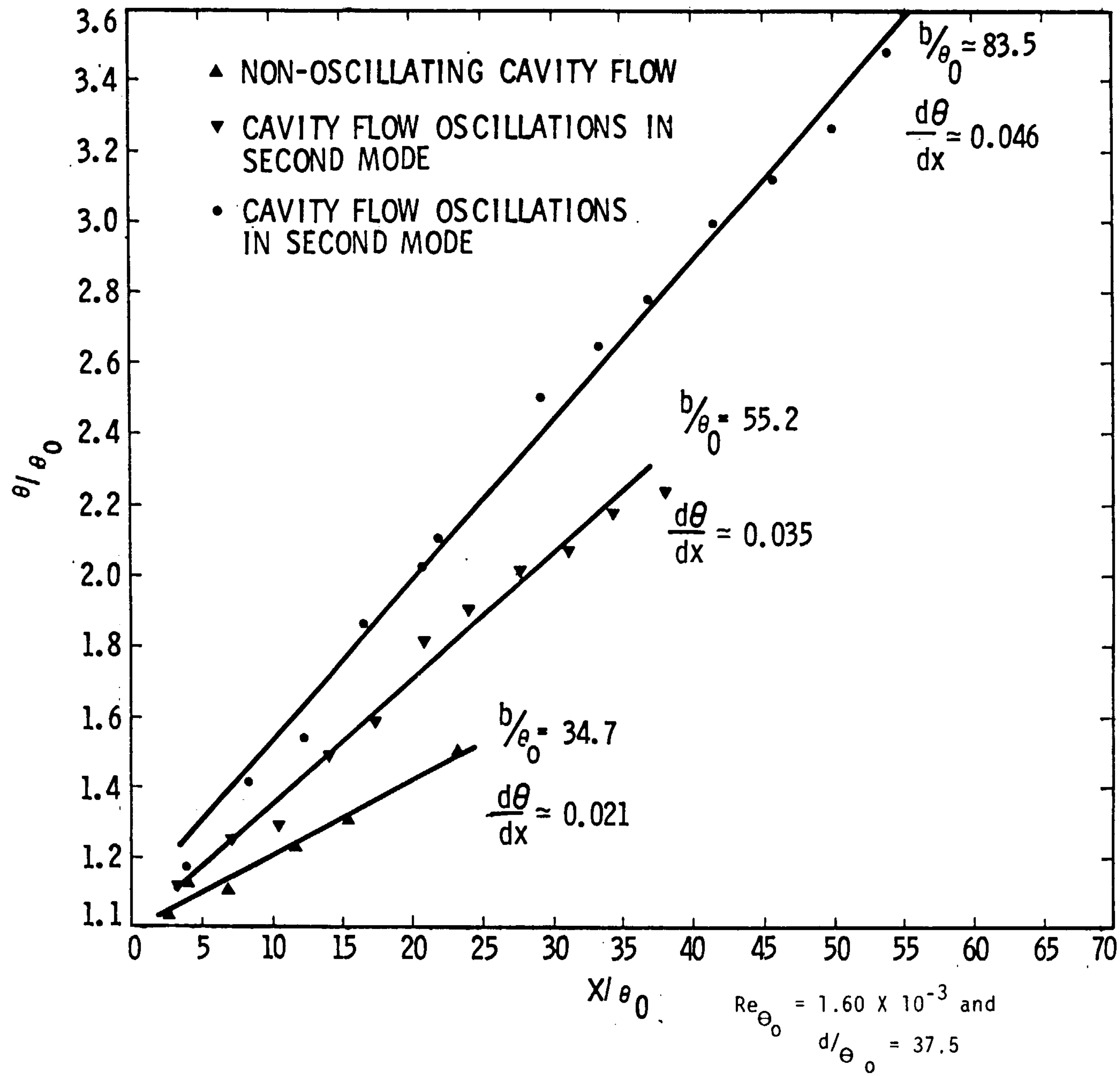


Figure 8. Effect of cavity width on shear layer growth.