Experimental Results of Large-Scale Structures in Jet Flows and Their Relation to Jet Noise Production

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Experiments have been performed to determine the role of large-scale turbulent structures in the production of jet noise. Axisymmetric turbulent jet flows at ambient stagnation temperature have been observed with the aid of flow visualization techniques. Jet Mach numbers at the nozzle exit ranged between 0.1 and 0.9 and the Reynolds number, based on nozzle exit diameter, was approximately 10^6. Large, organized turbulent structures existed as far downstream of the nozzle exit as 7 diameters. High-speed Schlieren motion pictures synchronized with near-field pressure measurements of an excited jet indicated that strong instantaneous peaks in the pressure signal occurred whenever a merging process between two large-scale organized structures occurred. This pressure pulse propagated at a speed which was somewhat larger than the velocity of the jet at the nozzle exit.

I. Introduction

REALIZATION of the presence of organized large-scale structures in turbulent shear flows has generated a growing interest in advancing the understanding of their role in the production of jet noise. Bradshaw et al.,[1] observed organized structures in jet flows; and this was further confirmed by Crow and Champagne.[2] More recently, Brown and Roshko,[3] Browand and Weidman,[4] and Winant and Browand,[5] recognized that the randomly merging and amalgamation process accompanying the evolution of these orderly structures in turbulent shear flows are responsible for entrainment and mixing, and are also largely responsible for the production of Reynolds stresses.

From space-time correlation results of different frequency bands of near-field pressure signals, Mollo-Christensen[6] showed that there was very little similarity with increasing separation distances between two microphones. From these results, Mollo-Christensen concluded that turbulence comes in packages and different frequencies preserve their phase over definite spatial distances along the jet flow. These results can be interpreted to mean that the turbulence responsible for the production of jet noise may be more organized than was realized before. Roshko[7] further showed that due to the distribution of the eddy life span in a turbulent shear flow, the associated velocity and pressure fluctuations may seem random even though their origin is quite organized. It should also be recollected that the dominant acoustic wavelength of the radiated jet noise spectrum is of the order of the jet diameter. This may be an indicator that the jet noise source has a length scale compatible with that of the large-scale structures, as has been observed visually in jet flows. All of these observations point strongly to the need for closer scrutiny of the jet noise sources and for the significance that these organized large-scale structures may have in the production of jet noise.

As pointed out by Ffowcs-Williams[8] and as implied by Peterson et al.,[9] the influence on noise generation of the large coherent structures in jet flows is as yet unknown. Since these turbulent structures can, however, be influenced by the acoustic field[2,10,11] and by the initial flow conditions,[12] they could possibly lead to the development of new methods of jet noise suppression techniques, providing that they do indeed contribute to noise generation.

Davies and Yule[13] stress the need for simultaneous flow visualization and measurements of physical flow quantities as a means to determine the manner in which these structures contribute to their influence on entrainment, transport, and on the production of noise. The present investigation was undertaken to advance the understanding of noise generation by such structures. The 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 characteristic large-scale structures and the production of jet noise.

II. Experimental Facility and Measurements

For the present investigation, air at room stagnation temperature was expanded through a subsonic nozzle into an anechoic chamber. The nozzle had an exit diam of 5.4 cm. The Reynolds number of the jet, based on nozzle exit diameter Re_D ranged between 10^5 and 0.86×10^5 and the exit Mach number M_e ranged between 0.1 and 0.9.

In some of the experiments, the jet flow was excited by introducing disturbances at discrete frequencies into a plenum chamber located upstream of the nozzle.The frequency of these disturbances ranged between 100 and 2000 Hz. These upstream disturbances were generated by passing the flow through an electropneumatic transducer. The modulation of mass flow through the transducer could be varied by controlling the amplitude of the electrical input at a given frequency. The rms velocity fluctuation at the center of the nozzle exit could be varied from 2% to as high as 8% of the mean jet velocity over the range of frequencies investigated. As a consequence of these large amplitude controlled velocity fluctuations at the nozzle exit, organized vortex structures of a given frequency were artificially induced in the jet shear layer. The development of these artificially induced organized structures was investigated in order to understand how they influence the small-scale jet structures, the turbulent mixing by merging, the interaction with each other as they are convected downstream, and the role of these processes in the production of jet noise.

The jet flow was made visually observable by injecting CO_2 gas into the plenum chamber of the nozzle air supply. Still shadowgraphs were taken with a spark source that had a time duration of approximately 1.0 μs. An experimental setup was devised to simultaneously investigate the near-field pressure oscillations and the visualization of the jet flowfield. This arrangement is shown in Fig. 1. A two-mirror Schlieren system with a 38×38 cm field of view was used as shown and

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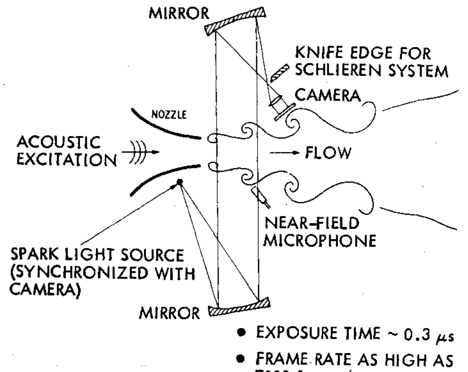

Fig. 1 Schematic diagram indicating the experimental setup.

high-speed motion pictures up to 7000 frames/s were taken of the jet. The spark source, which had a flash duration of 0.3 μs, was triggered by the camera. A total of 10 microphones with diameters of 3.18, 6.35, and 12.70 mm were mounted in a linear array in the near field just outside of the jet at an angle approximately 15 deg to the jet axis. The tips of this array of microphones were 3.5, 6.5, 9.0, 13.0, 16.5, 20.5, 25.0, 30.0, 36.5, and 43.5 cm, respectively from the nozzle exit. These microphones, however, are not shown in Fig. 1. They were carefully located approximately half a jet diameter outside of the jet mixing layer so that they did not disturb the jet flow. To obtain synchronization between the near-field pressure and the jet structure, a photocell was placed near one of the mirrors. The output of the photocell, together with the microphone signals, were recorded on a tape recorder. Thus the near-field pressure could be analyzed simultaneously with the movies on a frame-by-frame basis.

III. Experimental Results and Discussion

Flow Visualization

A spark shadowgraph showing organized large-scale structures in a nonexcited jet flow at a nozzle exit Mach number, $M_e = 0.69$ and a Reynolds number $Re_D = 0.4 \times 10^6$ is shown in Fig. 2. This figure also indicates the presence of large characteristic structures as far as 5-7 jet diameters downstream of the nozzle exit. These downstream strucutres bear a relation to the ones formed close to the nozzle exit. Thus, if the presence of organized large structures contribute to jet noise, the initial flow conditions of the jet at the nozzle exit may have an important role in controlling jet noise sources for several diameters downstream of the nozzle exit plane. As shown by the present authors,[14] the presence of the external boundary-layer flow over the engine cowl under flight conditions possibly may not alter the jet flow at the nozzle exit, as compared to a stationary nozzle without outer flow. Consequently, forward flight will not modify the organized large-scale structures and, hence, will not influence the jet noise sources at least for a distance of several jet diam. Therefore, there would not be an appreciable reduction of jet noise in flight, which is in agreement with flyover data.[15]

It is apparent in Fig. 2 that the spacing between the characteristic large-scale structures approximately doubles as they propagate downstream. High-speed motion pictures of jet flows showed that this doubling of the spacing between the organized structures was preceded by a merging process similar to one shown for incompressible flows by Brown and Roshko[3] and others.[4,5,9,10,12] For a motion picture framing rate of 7000 frames/s, the merging process between the organized structures occurred simultaneously many times at a relatively fast rate. Thus, it was not possible to investigate in detail the contribution of this merging process to the near-field pressure signal. To overcome this difficulty, organized structures of controllable frequency and amplitude were introduced artifically. Thus, the process of formation and merging could be slowed down by an order of magnitude. This was accomplished by introducing mass-flow fluctuations in the plenum upstream of the nozzle which, in turn, produced mass-flow fluctuations over the mean jet flow at the nozzle exit. This mass-flow fluctuation in the plenum chamber was also accompanied by the production of strong acoustic waves of frequency f. The transmission of this acoustic energy through the nozzle exit produced strong pressure signals both in the near field and the far field. However, in between the time intervals of these strong periodic acoustic waves which resulted from the introduction of the mass-flow fluctuations in the plenum, four to six small organized structures (depending on the introduced frequency f) appeared in the jet flow periodically at the nozzle exit. It is the interaction of these "in-between" organized structures that was investigated. It should be emphasized that the dynamics and the interaction processes among these artifically introduced organized structures were quite similar to those occurring in nonexcited jet flows. It is therefore believed that the study of the various processes associated with these organized structures under controlled experimental conditions is useful

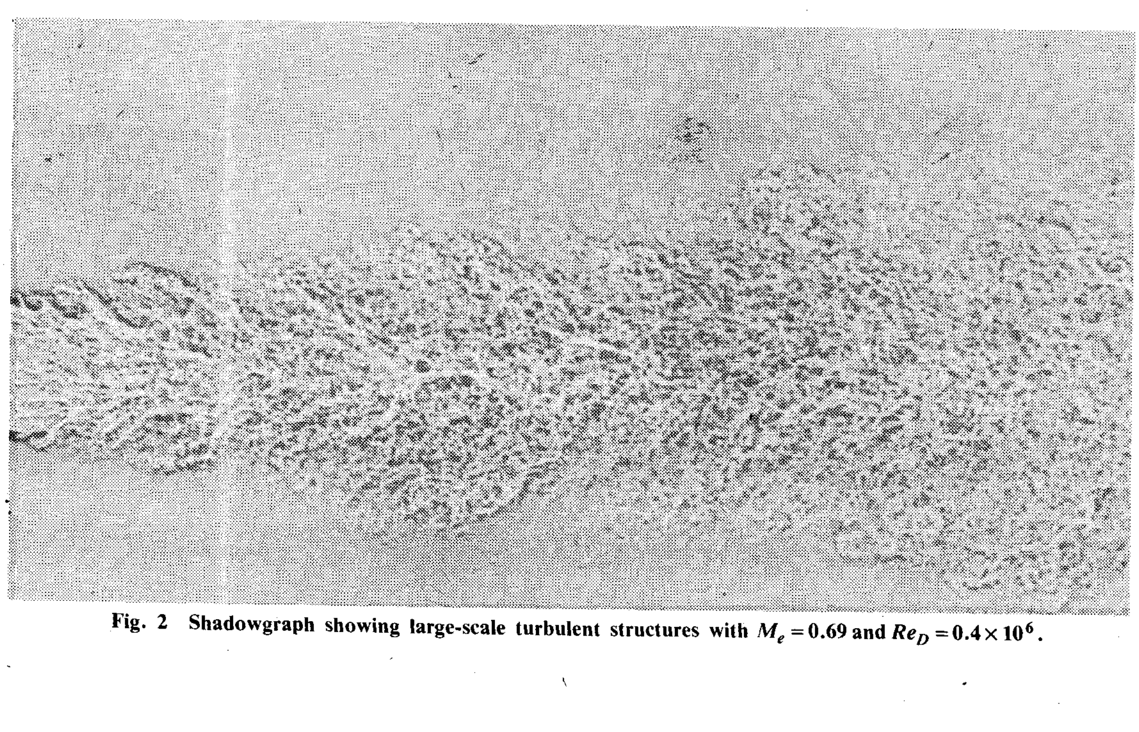

Fig. 2 Shadowgraph showing large-scale turbulent structures with $M_e = 0.69$ and $Re_D = 0.4 \times 10^6$.

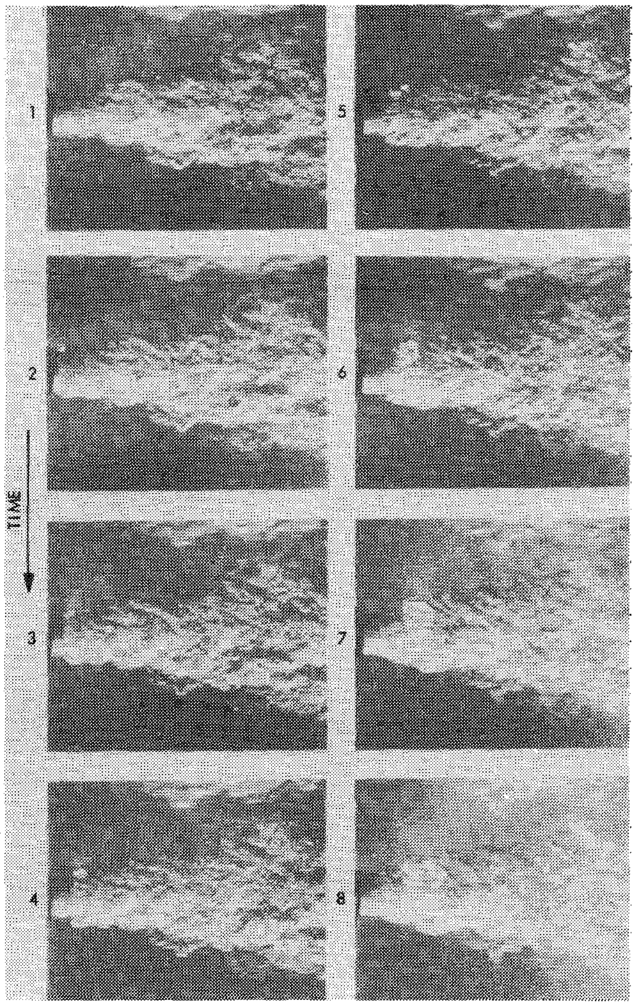

Fig. 3 A sequence of high-speed Schlieren motion pictures of an excited jet flow at $M_e = 0.44$ and $fD/U_e = 0.14$. Duration between frames $\simeq 140\ \mu s$.

in identifying the role of large-scale structures in the production of noise in nonexcited jet flows.

A typical sequence of Schlieren motion pictures showing the behavior of artifically introduced large-scale organized structures is shown in Fig. 3. The exit Mach number, M_e, was 0.44 and the nondimensional frequency, fD/Ue, was 0.14. The quantity f is the input frequency of the fluctuating mass flow in the plenum chamber. In this sequence of pictures, the time duration in between the frames was approximately 140 μs, during which an introduced organized torroidal vortex structure travelled approximately 15-20% of the nozzle exit diam. The lower jet mixing layer in the second frame shows a vortex structure that formed near the nozzle exit. This same vortex structure is identifiable in subsequent frames and it is apparent that its size increases at later times in frames 3, 4, and 5. Also on these frames other organized vortex structures can be seen which were shed earlier. In frame 5 of Fig. 3, the first two vortices can be seen side-by-side and are almost close enough together to merge with each other. These two vortices began to merge at about the time that frame 6 was taken. The merging process was actually completed between the time that frames 6 and 7 had been taken. The merged structure then propagated downstream, as can be seen on frames 7 and 8. This process was repeated whenever a new vortex was shed from the nozzle exit. One can also observe on frame 5 of Fig. 3 that the spacing between the vortices doubles as they convect downstream, as has been observed by Moore[10] in nonexcited jet flows.

The salient features of the presence of the artificially introduced, organized large-scale structures in jet flows are summarized as follows:

1) The time taken for the merging process of two organized vortex structures to occur was about 10% of their life span in the jet flow.

2) The merging process was initiated by the upstream vortex contracting in size, while the downstream one adjacent to it simultaneously expanded radially outward. This was accompanied by a rotation of these two vortices around each other and the merging was thus completed. Similar behavior of organized vortex structures was observed by Laufer[16] in round waterjet flows with dye injection.

3) Under similar nozzle flow conditions, an increase in the growth of the jet, viz., the jet spreading angle, was observed when the jet flow was excited by the introduction of controlled organized vortex structures, as compared to nonexcited jet flows (see Fig. 6).

Near-Field Pressure Measurements

Figure 4 shows successive frames of Schlieren motion pictures of an excited jet flow at approximately 5000 frames/s, along with the near-field pressure output signal of microphone C. The Mach number of the jet at the nozzle exit was 0.44 and the Reynolds number was 0.64×10^6. The nondimensional frequency, $S \equiv fD/Ue$, was 0.14. The pressure signal associated with the input frequency is indicated by the high peak at the left in Fig. 4. The distribution of the pressure signal to the right of the first peak in the near field shown is associated with the vortices that were found in between those generated by the input frequency.

In Fig. 4, it appears that the microphones were located inside the jet stream. Actually, they were about one nozzle exit radius outside the flowfield. The erroneous impression in this respect is a result of the angle of view of the motion picture camera.

In Fig. 4, the first pressure wave, which is a result of the high amplitude input wave, can be seen in the pictures of frames 2, 3, and 4. This strong acoustic wave is sensed again by microphone C approximately 2.2 ms later for the flowfield corresponding to the one in frame 12. In between this time interval (between frames 2 and 12), the microphones sensed primarily the pressure field generated by the dynamics of the artificially introduced organized structures as well as the normally produced jet noise. The similarity of the behavior of the organized structures in Fig. 4 with those previously discussed in Fig. 3 is apparent. A large characteristic vortex passed below microphone C in frame 4 of Fig. 4, but it did not significantly change the near-field pressure signal. This is a significant observation which implies that a single convecting organized vortex is a very weak source of jet noise in the near-field pressure. This organized structure then interacted with another vortex nearby, as can be seen in frame 7 of Fig. 4. Instantaneously, the microphone showed a slow decrease in the pressure, followed by a relatively rapid-rising strong pressure signal. As this pressure pulse propagated away from microphone C, the amplitude of the microphone output signal did not show any significant change, even though other organized vortices convected past it without merging with adjacent ones.

Results in Fig. 5 show the simultaneous jet flow structure and the near-field pressure data of microphone C as just discussed, along with the data of microphones A, D, E, and F. These microphone output signals were selected to show the salient features of a merging process of organized large-scale vortices. It should be noted that the outputs of all the microphones in Fig. 5 have not been normalized. The propagation of a pressure pulse generated with the corresponding flow shown on frame 7 of Fig. 5 can be seen to be the result of a merging process between two organized vortices. This pressure pulse, as was also discussed with respect to Fig. 4, is sensed at a later time by microphones D, E, and F. The slope of the line joining the peaks of these

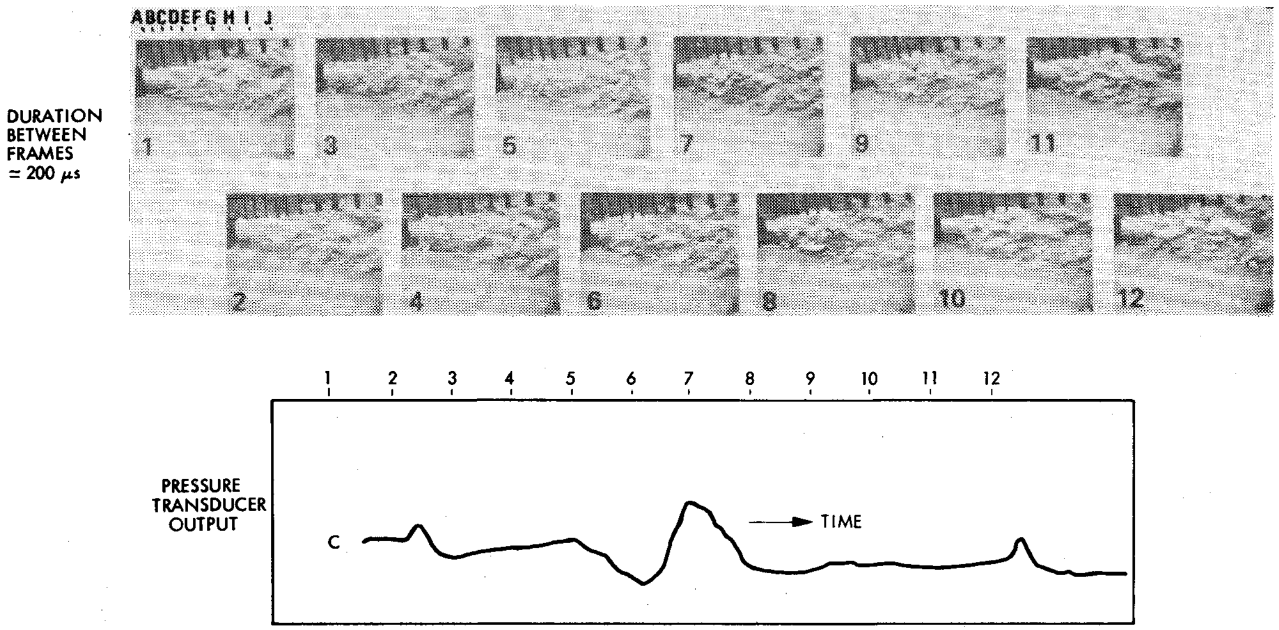

Fig. 4 A sequence of high-speed Schlieren motion pictures of an excited jet along with a near-field pressure signal at $M_e = 0.44$ and $fD/U_e = 0.14$. Duration between frames $\simeq 200$ μs.

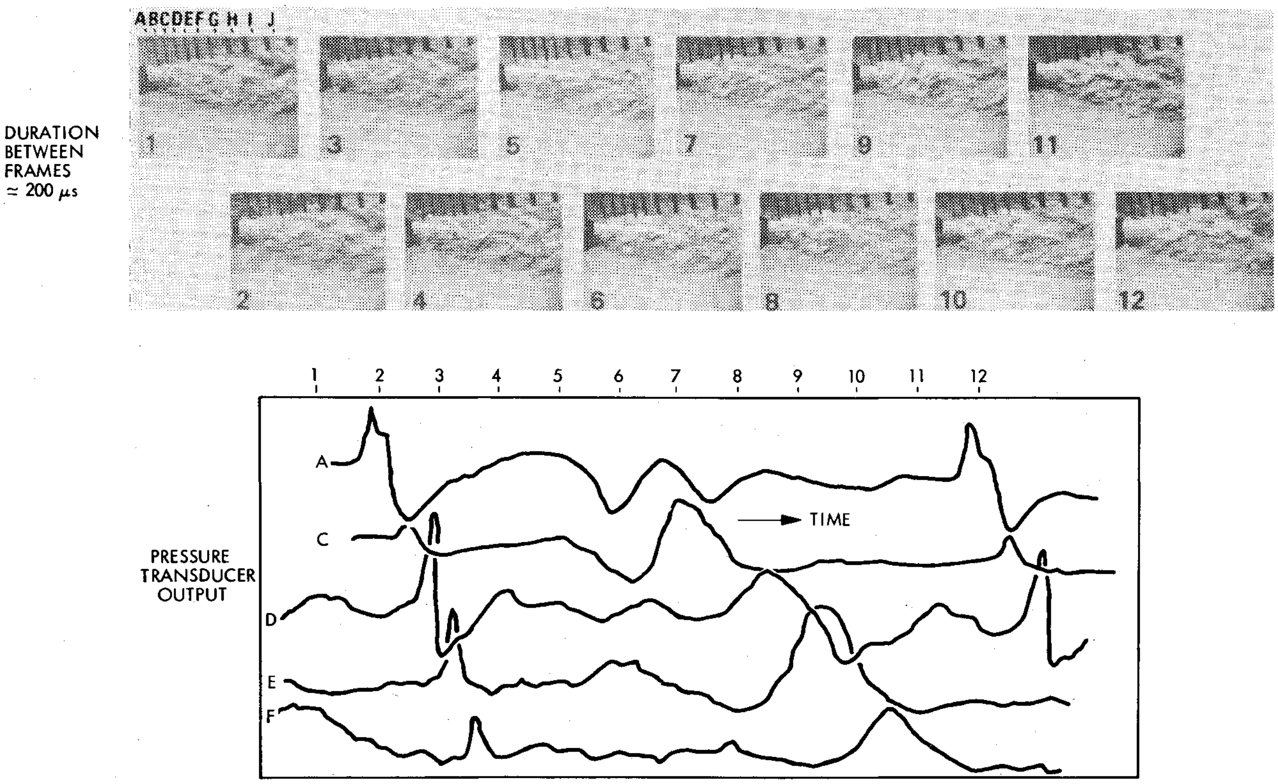

Fig. 5 High-speed Schlieren motion pictures of an excited jet along with a series of near-field pressure signals at $M_e = 0.44$ and $fD/U_e = 0.14$.

pressure pulses determines the propagation speed of the pressure pulses. For this particular case, the average propagation speed of this pressure pulse c relative to the ambient speed of sound was approximately $c/a_\infty \simeq 0.51$. It should be recognized that this propagation speed was higher than the jet exit Mach number of 0.44. In other words, this peak should not be confused with the convection of the merged vortex structure past microphones D, E, and F. These experimental results indicate that a significant part of the near-field pressure signal was contributed by the interaction (or merging) of the large organized structures in the jet flow.

Mean Velocity Measurements

Experimental results which show the influence of the organized large-scale structures of a jet flow on the mean jet velocity profile are shown in Fig. 6. In this case, the Mach number at the nozzle exit was 0.60. For all tests, both excited and nonexcited flows, the flow passed through a pneumatic transducer located upstream of the nozzle. When this transducer was not energized (nonexcited jet flow), the rms velocity at the nozzle exit was about 2% of the mean exit velocity and was random in nature. However, when the pneumatic transducer was energized to produce an excited jet flow with ar-

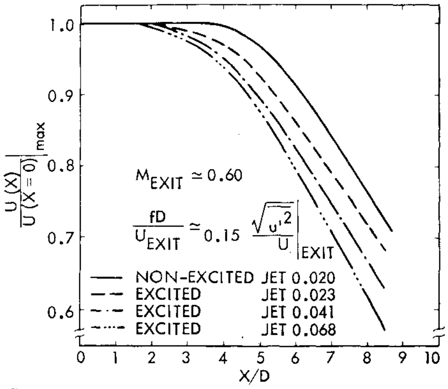

Fig. 6 Influence of flow excitation at nozzle exit on the mean velocity at the jet centerline.

tificially generated, organized vortex structures, these velocity fluctuations were periodic at the nozzle exit. With periodic velocity fluctuations at the nozzle exit of 2.3% of the mean exit velocity at $fD/Ue = 0.15$, the mean jet velocity at the centerline decayed more rapidly than for the corresponding nonexcited jet. In fact, as can be seen in Fig. 6, the length of the potential core was reduced by almost half the length of a nonexcited jet. As the magnitude of the velocity fluctuations at the nozzle exit was increased by energizing the pneumatic transducer to higher amplitude mass-flow fluctuations, the mean velocity of the jet at the centerline decayed even more rapidly. As a consequence of these results, it is concluded that the presence of organized large-scale structures and their interactions with each other are greatly responsible for entrainment and mixing in jet flows.

IV. Concluding Remarks

The present experimental results showed that a significant part of the pressure signal in the nearfield was contributed by the interaction and merging processes of large-characteristic organized structures in the jet flows. The portion of this nearfield pressure signal which radiates to the farfield is an important aspect of this problem that needs future attention. Since this merging process has a statistical distribution of length and life span,[7] it is quite probable that the emitted jet noise in the fairfield from such a source may appear to be broadband. Mollo-Christensen[6] has also postulated that noise emitted may be in packets and that their source may be more coherent than has been anticipated in the past. It is believed from the present experimental results that methods in which the merging processes among organized structures are subdued could lead to jet noise reduction.

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