Coherent Large-Scale Structures in High Reynolds Number Supersonic Jets

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The objective of this study was to investigate the existence of large-scale coherent structures in high Reynolds number, shock-free supersonic jets. The experiments were conducted for a fully expanded jet $M_j = 1.4$ and $Re_j = 1.6$ million. To extract the large-scale structure from within the random turbulence, the jet was excited by a very weak upstream tone. The important results derived from this particular study can be summarized as follows: 1) large-scale structures do exist in a high Reynolds number, fully expanded jet of $M_j = 1.4$, 2) the most preferential Strouhal number (St_j) for these structures is in the vicinity of 0.4, and 3) the dependence of the large-scale structure phase velocity on the excitation Strouhal number shows the same trend as found for subsonic tone-excited jets.

Nomenclature

a = sound velocity
b = shear layer half-width
D = nozzle diameter
f = frequency
i = turbulence intensity $\left(\sqrt{\overline{u'^2}} \Big/ U_j\right)$
M = Mach number
St = Strouhal number $(f \cdot D_j / U_j)$
R = nozzle radius
Re = Reynolds number $(U_j \cdot D_j / \nu)$
t = time
U = mean velocity
u' = fluctuation velocity
X = axial distance
Y = radial distance
ϕ = phase
τ = time period
ν = kinematic viscosity

Subscripts:
A = amplitude
c = phase velocity
e = excitation
j = jet
s = strobe
u = axial velocity
o = ambient

Introduction

OVER the last 15 years, a considerable experimental effort has been devoted to the study of the behavior of large-scale, coherent structures in low-speed, subsonic jets.[1-7] A limited number of studies have also been conducted to understand these structures in fully expanded supersonic jets, but they have been restricted to low Reynolds numbers.[8-13] However, in supersonic, fully expanded, high Reynolds number jets, the existence of large-scale, organized, coherent structures in the jet shear layers has, until recently, remained in question. The objective of this program was to determine, through experimentation, whether large-scale coherent-like structures exist in high Reynolds number, shock-free supersonic jets, and if so, to determine some of their characteristics.

Method of Approach

To achieve the stated objective, a systematic set of flow visualization experiments and quantitative flow measurements of a supersonic, fully expanded jet of $M_j = 1.4$ were made in the freejet research facility of the Lockheed-Georgia Company. The facility, shown in Fig. 1, consists of a 256-mm-diam plenum followed by an initial contraction to a 102-mm-diam, 340-mm-long source-section duct. The 50.8-mm-diam convergent/divergent test nozzle is attached to the source-section duct. The plenum to nozzle area contraction ratio is 25. To extract the large-scale structure from within the random turbulence in the jet shear layer, the jet is excited by an upstream tone generated in a source section. The source section consists of eight acoustic drivers, coupled in pairs, equally spaced along the circumference of the nozzle supply duct. The source section utilizes 100-W Altec model 290E acoustic drivers. The sound is funneled to the nozzle supply duct through four 25.4-mm-diam tubes. Each tube is connected to a pair of acoustic drivers through a "Y" connector. The root mean square voltages fed to the acoustic drivers are used to denote the strength of excitation instead of true excitation sound pressure levels, because it was found difficult to make reliable measurements of the excitation levels at the center of the nozzle exit plane of the supersonic jet. For the experiments described in this paper, the sound pressure levels, measured just outside the nozzle lip with the jet running, were 119 ± 2 dB.

Advanced experimental methods were used to perform the planned experiments. Flow pictures were acquired using a unique laser Schlieren system that enabled photographic ensemble averaging, thereby revealing the existence of the large-scale turbulent structure in the jet shear layer.[14,15] Lockheed's laser velocimeter system with conditional sampling[16,17] was used for flowfield measurements in order to quantify the qualitative results obtained in the flow visualization task. More details of the test facility and the data acquisition and reduction procedures are given in Ref. 6.

Since no experimental results on the behavior of large-scale structures in supersonic, fully expanded, high Reynolds number jets have been published in the open literature, a direct

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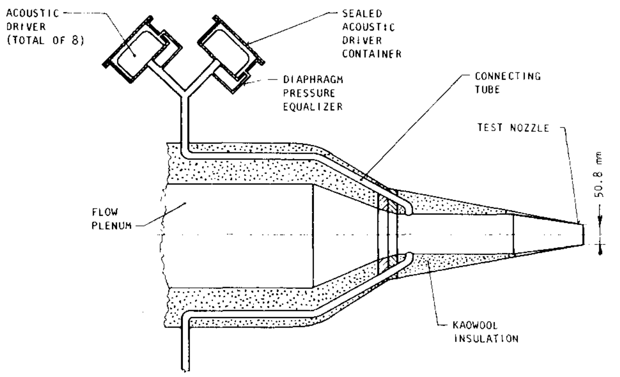

Fig. 1 Test facility.

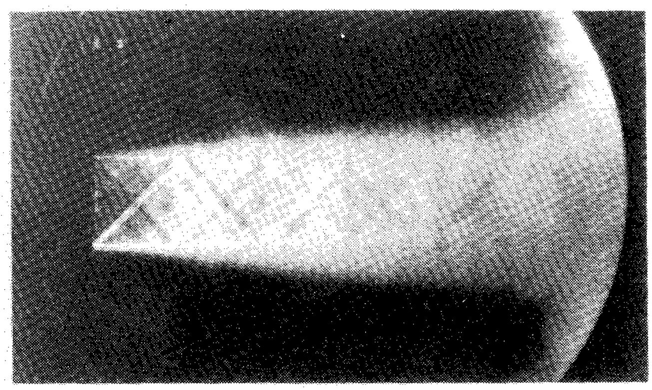

Fig. 2 Ensemble-averaged photograph of an unexcited jet; $f_s = 3125$ Hz, $\phi = 0$ deg.

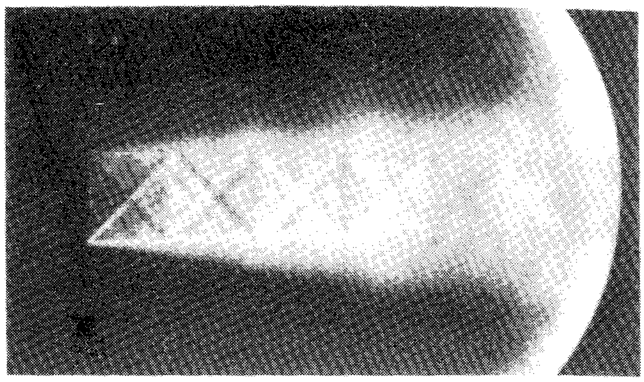

Fig. 3 Ensemble-averaged photograph of an excited jet, $M_j = 1.37$, $St_j = 0.3$, $f_s = 2348$ Hz, $\phi = 0$ deg.

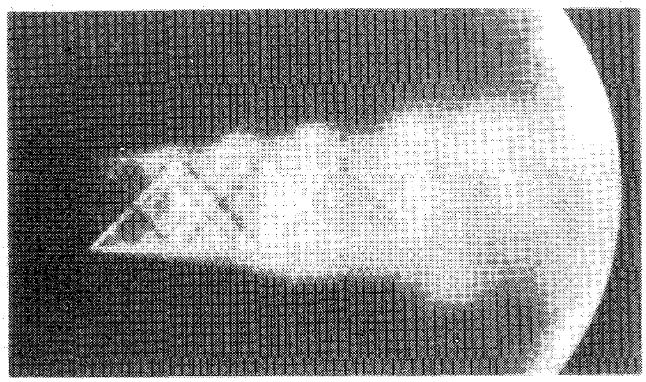

Fig. 4 Ensemble-averaged photograph of an excited jet, $M_j = 1.37$, $St_j = 0.4$, $f_s = 3128$ Hz, $\phi = 0$ deg.

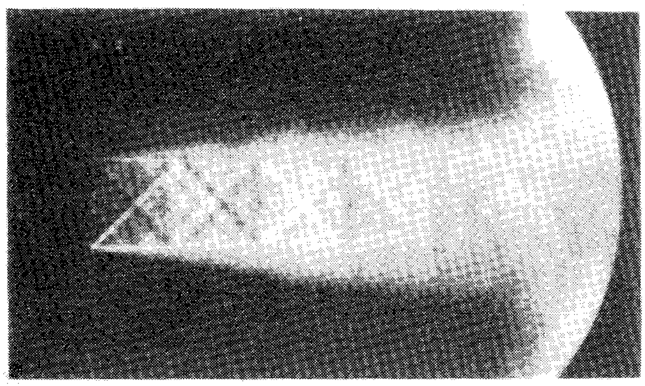

Fig. 5 Ensemble-averaged photograph of an excited jet, $M_j = 1.37$, $St_j = 0.6$, $f_s = 4667$ Hz, $\phi = 0$ deg.

comparison of the present experimental data with the results of others is not possible. Therefore, the present data are compared with either the experimental results for low Reynolds number supersonic jets or the results for high Mach number subsonic jets.

Experimental Results

Flow Visualization

The flow visualization task started with an experiment on excitation Strouhal number (frequency) effects. The purpose was to determine the most preferential Strouhal number for the coherent large-scale structures in the shear layer of a supersonic jet of $M_j = 1.4$. The jet was excited in a frequency range of $f_e = 1547$–6228 Hz. This frequency range corresponds to the excitation Strouhal number range of $St_j = 0.2$–0.8.

Ensemble-average Schlieren pictures of the fully expanded supersonic jet of $M_j = 1.4$ are shown in Figs. 2–5. These figures cover the flow structure development along the first six nozzle exit diameters. As seen in Fig. 4, at the excitation Strouhal number of 0.4, humps along the jet shear layer boundary are visible. This indicates the presence of a periodic structure in the flow synchronous with the triggering frequency.

The second experiment in the flow visualization task was the time delay experiment. The time delay measurements were made to determine the development of the large-scale structure. The spatial development during one period of the triggering signal was used to calculate the large-scale structure phase velocity. The phase velocity was calculated from the distance traveled by the large-scale structure (measured on ensemble-averaged photographs) during a known time interval (the phase or time delay of the strobing light with respect to the excitation signal). A series of pictures with a constant phase shift of 60 deg for a jet excited at a Strouhal number of 0.4 is shown in Fig. 6. The results of time delay experiments are summarized in Fig. 7, where the phase velocity, normalized by the nozzle exit velocity, is plotted as a function of the jet excitation Strouhal number. The phase velocity is shown to be a function of the Strouhal number in this figure.

Flow Measurements

Quantitative flow velocity measurements using the laser velocimeter were focused on two tasks. The first task consisted of measurements of mean velocity and mean turbulence intensity along the jet centerline and jet radials at four axial locations. The mean velocity and mean turbulence intensity distributions along the jet centerline for both unexcited and

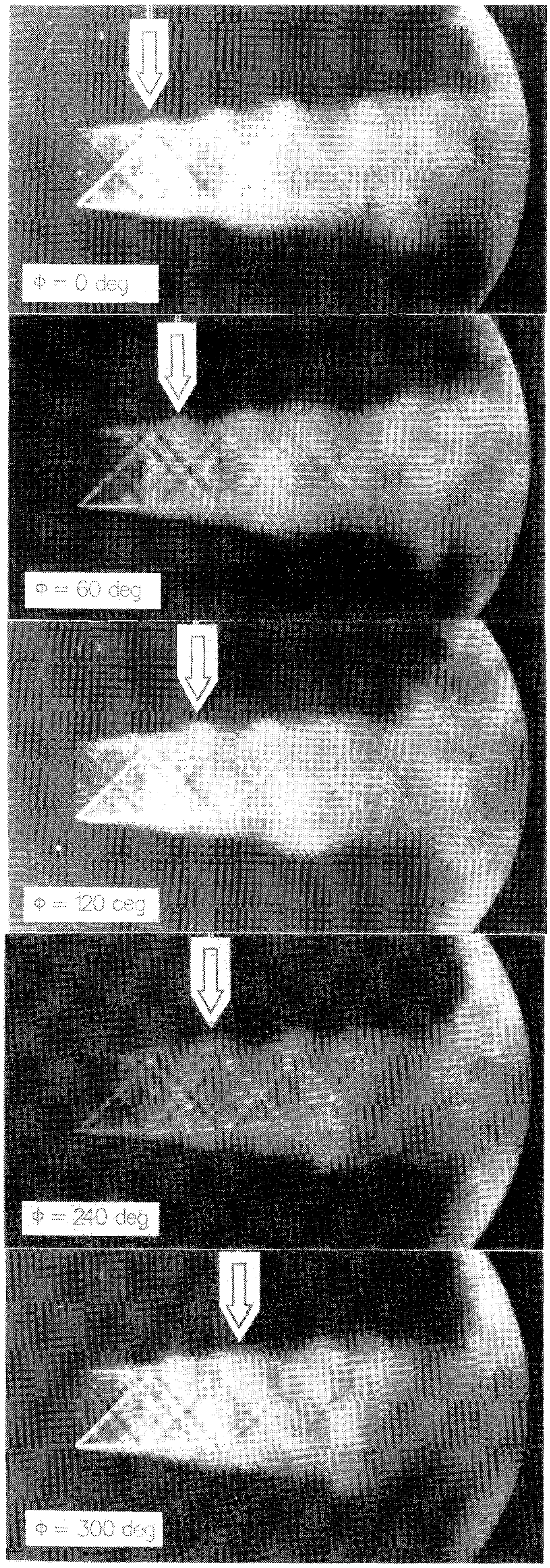

Fig. 6 Ensemble-averaged photograph of an excited jet, $M_j = 1.37$, $St_j = 0.4$, $f_s = 3125$ Hz.

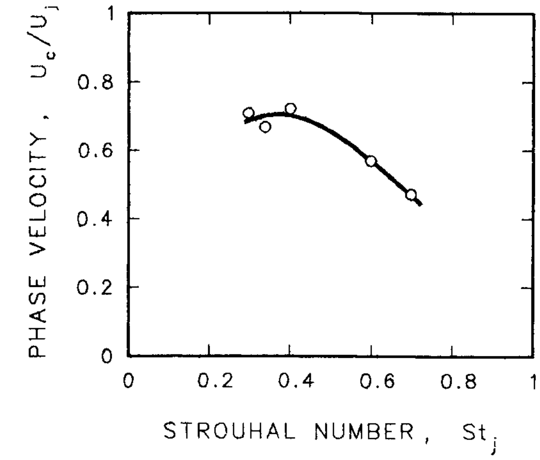

Fig. 7 Variation of large-scale structure phase velocity with excitation Strouhal number.

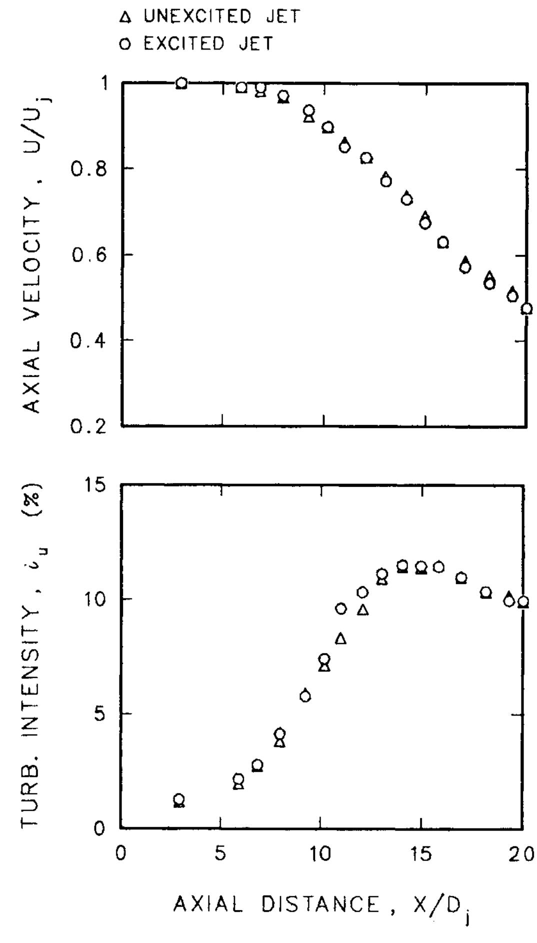

Fig. 8 Mean velocity and turbulence intensity centerline profiles of a fully expanded supersonic jet of $M_j = 1.38$, $U_j = 454$ m/s.

excited jets are plotted in Fig. 8. The radial profiles for $X/D_j = 3$ and $X/D_j = 9$ are shown in Figs. 9 and 10. As seen from these figures, there is no significant difference between the excited and unexcited jet mean velocity and turbulence intensity distributions. Thus, the excitation tone that served as a triggering signal for acquiring conditionally sampled laser velocimeter data did not measurably alter the mean velocity and turbulence intensity characteristics of the jet itself.

The second task was planned to measure the periodic velocity component. This proved to be a very difficult task

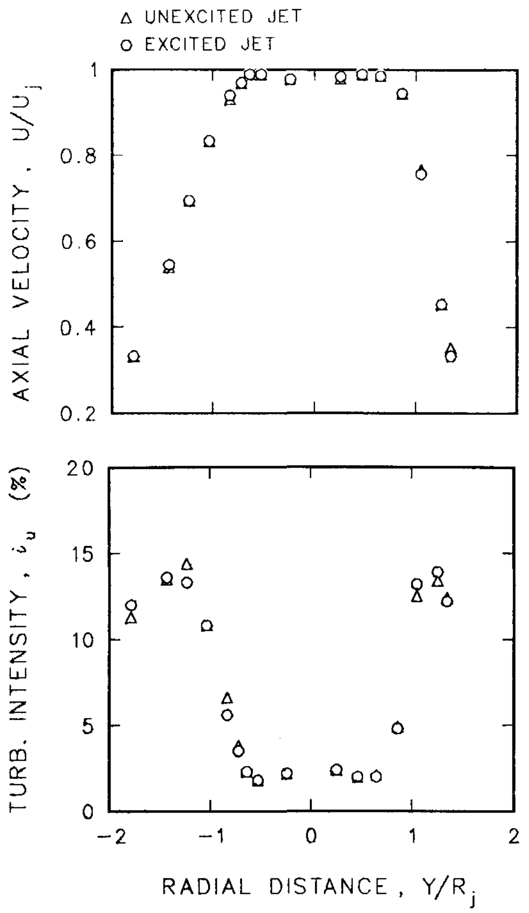

Fig. 9 Mean velocity and turbulence intensity radial profile of a fully expanded supersonic jet of $M_j = 1.38$, $U_j = 454$ m/s at $X/D_j = 3$.

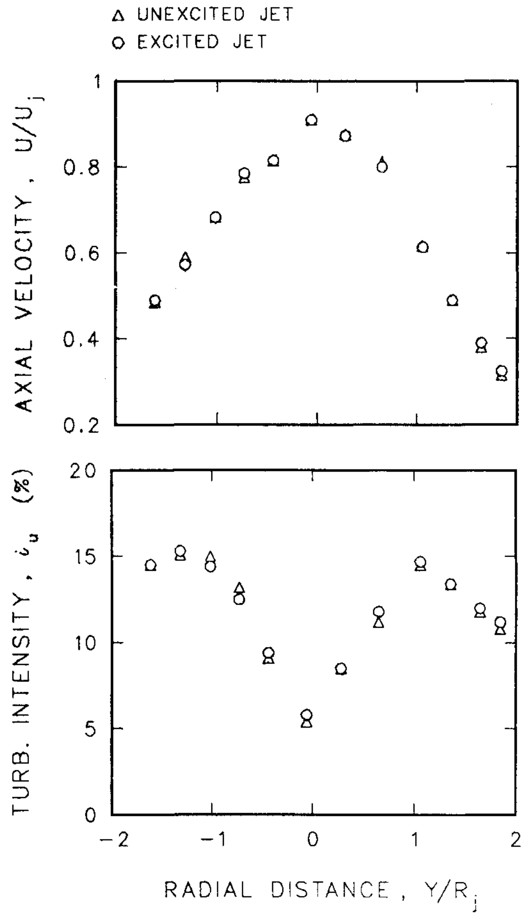

Fig. 10 Mean velocity and turbulent intensity radial profiles of a fully expanded supersonic jet of $M_j = 1.38$, $U_j = 454$ m/s at $X/D_j = 9$.

because of the low intensity of the velocity fluctuations in the large-scale structure. The periodic velocity time distributions in most cases were contaminated with very intense background noise attributable to a low laser velocimeter data rate in the supersonic jet, especially in the shear layer region. The results achieved at the jet centerline are shown in Figs. 11 and 12. As seen in Fig. 11, there are no traceable periodic fluctuations in the flow at $X/D_j = 5$. At another location, $X/D_j = 7$ (Fig. 12), it is seen that the large-scale structures generate velocity fluctuations of the period of $\tau = 280$ μs, which corresponds to the excitation Strouhal number of 0.4. The amplitude of the periodic velocity fluctuations, however, is very small, less than 1% of the jet exit velocity. For the jet exit velocity of 454 m/s, the corresponding intensity of periodic fluctuations is 0.6%. As seen in Fig. 8, the total turbulence intensity at $X/D_j = 7$ is 2.9%. Thus it appears that the level of periodic fluctuations reaches approximately 20% of the total turbulence intensity at the centerline location of $X/D_j = 7$.

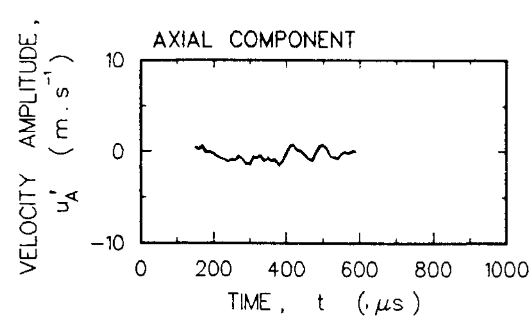

Fig. 11 Ensemble-averaged velocity data measured on jet centerline at $X/D_j = 5$.

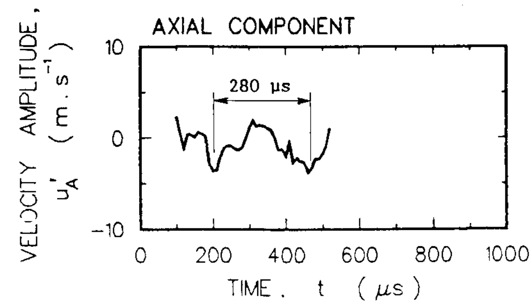

Fig. 12 Ensemble-averaged velocity data measured on jet centerline at $X/D_j = 7$.

Comparison with Existing Measurements

Whereas the importance of the large-scale turbulence in subsonic-jet mixing layers is generally recognized and well-documented, no experimental results on the behavior of large-scale structures in supersonic, fully expanded, high Reynolds number jets have been published in the open literature. Therefore, the direct comparison of present experimental data with the results of others is not possible; however, the present data are compared with either the experimental results for low Reynolds number supersonic jets or the results for high Mach number subsonic jets.

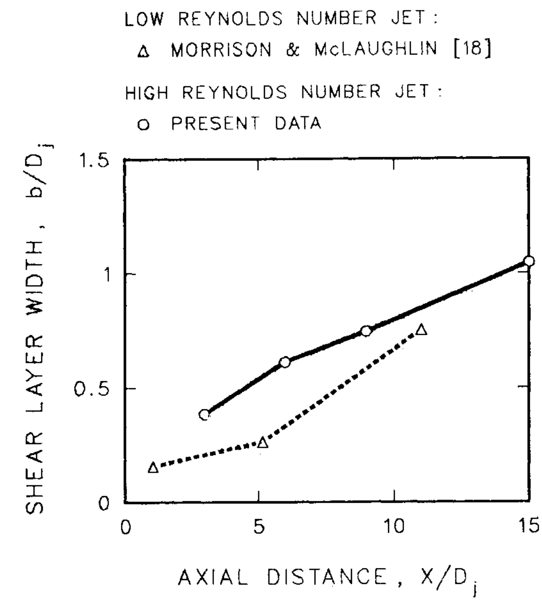

Fig. 13 Variation of shear layer half-width parameter with downstream distance of a supersonic jet of $M_j = 1.4$.

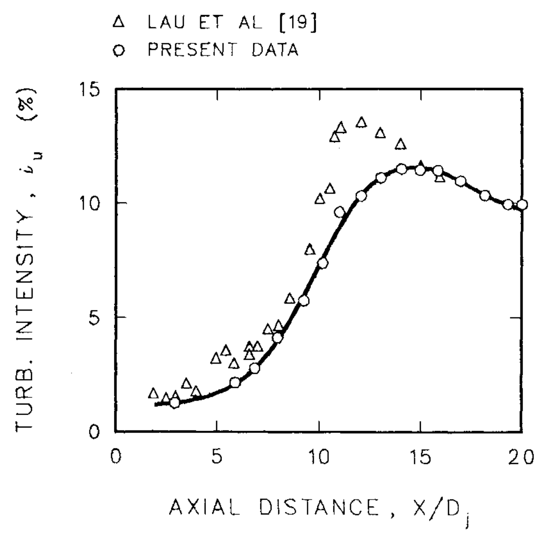

Fig. 14 Comparison of centerline distributions of total turbulence intensity of supersonic jet of $M_j = 1.37$.

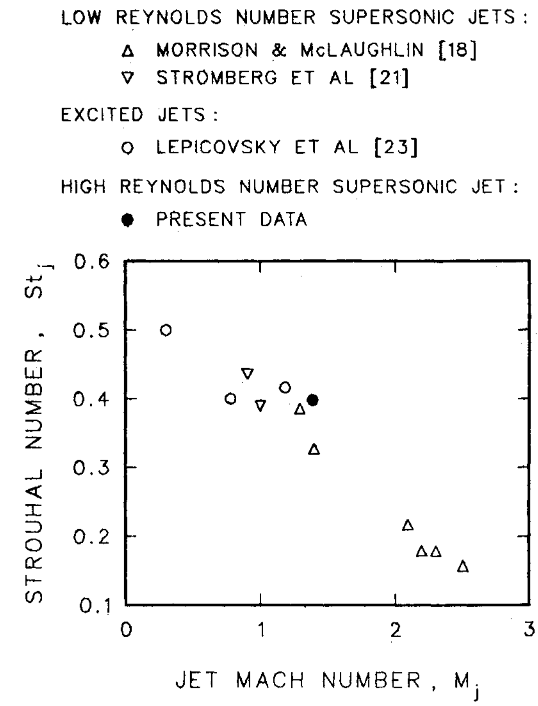

Fig. 15 Variation of dominant Strouhal number with jet Mach number.

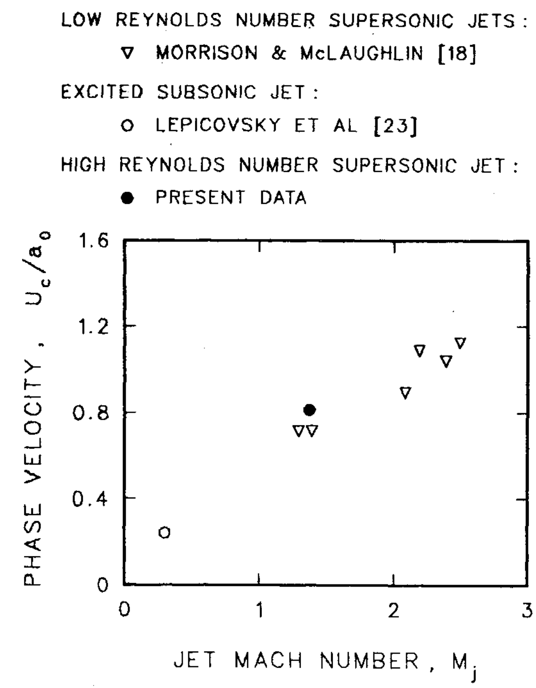

Fig. 16 Phase velocity of the dominant instability component as a function of jet Mach number.

Mean Flow Characteristics

Two mean flow parameters, namely the jet spreading rate and turbulence intensity centerline distribution, were compared with the measurements of Morrison and McLaughlin[18] and Lau et al.[19] These comparisons are shown in Figs. 13 and 14. Figure 13 shows how the shear layer half-thickness parameter b varies with downstream distance for the high Reynolds number jet (present data) and low Reynolds number jet (Morrison and McLaughlin[18]). When compared with the low Reynolds number jet, the spreading rate of the high Reynolds number jet shear layer is much higher initially but then slows down at the end of the jet potential core. It appears that the spreading rates of both low and high Reynolds number jets are approximately the same at great distances from the nozzle exit plane. The previously noted difference between the low and the high Reynolds number jets appears to be real. In fact, Morrison and McLaughlin[18] reported similar behavior on comparing their data for a low Reynolds number jet of $M_j = 2.5$ to the high Reynolds number jet analytical prediction of Morris and Tam.[20]

The centerline distribution of turbulence intensity was compared with similar measurements in a high Reynolds number jet of $M_j = 1.4$, reported by Lau et al.[19] This comparison is shown in Fig. 14. As seen in this figure, the data agree reasonably well in the region near the end of the jet potential core ($X/D_j = 7$). Beyond the potential core, in the region of $X/D_j = 10$–14, the present data tend to show lower turbulence levels than Lau's data. The reason for this discrepancy is not clear.

Instability Strouhal Number

In unforced jets, the instability Strouhal number is considered to be that which corresponds to the most dominant frequency naturally present in the velocity spectrum. It is generally believed that if a jet is excited at this Strouhal number, the jet response will be most pronounced. Conversely, the most preferred excitation Strouhal number of a jet should be equal to the jet instability Strouhal number.

Jet instability Strouhal numbers for low Reynolds number supersonic jets measured by Morrison and McLaughlin[18] are shown in Fig. 15. The data for a high-speed subsonic jet measured by Stromberg et al.[21] are also shown in this figure. The figure shows that the Strouhal number of the dominant instability has a strong Mach number dependence, particularly in the supersonic region.

Acoustically forced jets, at least for $M_j < 1.2$, tend to follow a similar trend. The data for acoustically forced subsonic jets measured by Lepicovsky et al.[23] and the data from the present work are also included in this figure. Clearly, the instability Strouhal number of the present data agrees very well with the results of similar measurements for a range of Reynolds numbers, indicating a similarity in the behavior of low and high Reynolds number jets.

Phase Velocity

The phase velocity of the dominant instability component as a function of the jet Mach number is shown in Fig. 16. Data in this figure are those measured by Morrison and McLaughlin[18] in supersonic, low Reynolds number jets excited at a very low level, and by Lepicovsky et al.[23] in a tone-excited, subsonic jet of $M_j = 0.3$. The present data tend to agree very well with the indicated trend.

If, however, the phase velocity is plotted as a function of the Strouhal number, strong differences are found among the existing experimental data. Figure 17 summarizes these findings. It should be mentioned that unlike in Fig. 16, where the phase velocity was normalized by ambient sound speed, the phase velocity in this figure is normalized by jet exit velocity. In Fig. 17, the phase velocity variation of unforced jets is shown by a broken line. This line represents the measurements of Armstrong and Ackermann as reported in Ref. 22. Independent measurements in unforced jets in the Mach number range of 0.17–0.7 agree very well with each other and show an increasing phase velocity with an increasing Strouhal number.

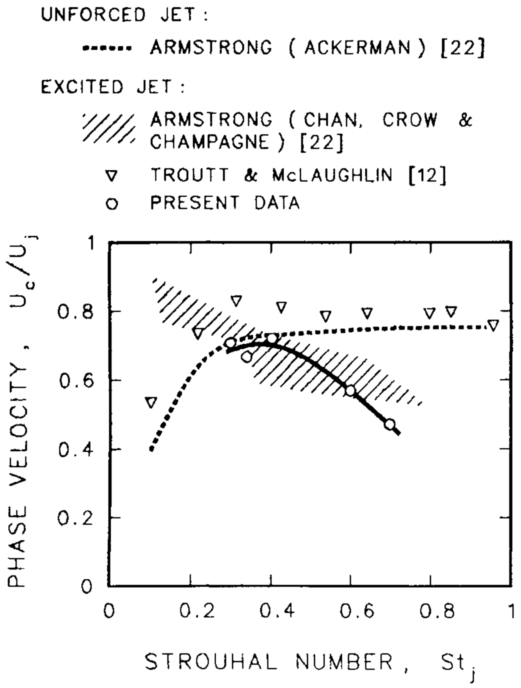

Fig. 17 Variation of large-scale structure phase velocity with Strouhal number.

Measurements in forced jets, however, show a decreasing phase velocity with an increasing Strouhal number. These measurements, performed by Chan and by Crow and Champagne in low Mach number jets (reported in Ref. 22), exhibit a higher scatter and are represented in Fig. 17 by the shaded area. Armstrong[22] attributes this discrepancy to a basic difference between the behavior of pressure waves in an unforced jet and in an acoustically forced jet.

The Troutt and McLaughlin data[12] of excited, moderate Reynolds number supersonic jets tend, however, to agree more with that for unforced jets. Troutt and McLaughlin found the axial phase velocity to be approximately constant for most of the Strouhal number range, with the exception that at the low-frequency end the phase velocity decreases considerably. As is also seen in Fig. 17, the present data for a high Reynolds number supersonic jet of $M_j = 1.4$ exhibit a decrease in phase velocity with increasing Strouhal number. No doubt the strength of the forcing and the actual mode of the excitation are of prime importance to this data comparison and may contribute to the indicated discrepancy.

Conclusions

Based on the reported experimental results, the following conclusions may be made:

1) The large-scale structures can be excited in fully expanded, supersonic, high Reynolds number jets, and they prevail even beyond the potential core of the jet.

2) The most preferential excitation Strouhal number for the large-scale structure in a fully expanded jet of $M_j = 1.4$ is in the vicinity of 0.4.

3) No significant difference, as far as the preferential Strouhal number is concerned, has been observed between the high- and low-Reynolds number fully expanded jets of $M_j = 1.4$.

4) The large-scale structure, excited under the present test conditions, was relatively very weak. The mean flow characteristics were not affected at all by this weak structure. It appears that under these conditions, the level of periodic fluctuations reaches at most 20% of the total turbulence intensity level on the jet centerline at the end of the jet potential core.

5) The dependence of the large-scale structure phase velocity on the excitation Strouhal number under the present conditions shows the same trend as that found for subsonic, acoustically excited jets.

Acknowledgment

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