Laser Velocimeter Measurements of Large-Scale Structures in a Tone-Excited Jet

J. Lepicovsky*
Lockheed-Georgia Company, Marietta, Georgia

The major goal of this study was to conduct laser velocimeter measurements of nonsteady velocities associated with the large-scale structure of a tone-excited jet. To accomplish this goal, data acquisition and reduction procedures were developed for a laser velocimeter, enabling conditional sampling and ensemble averaging. These procedures retrieved the fluctuating velocity history by synchronizing the beginning of the sampling interval of the laser velocimeter data with respect to the flow periodic oscillations. To verify the feasibility of the proposed procedure, extensive measurements were made in the shear layer of a jet excited by discrete tone sound produced upstream of the nozzle exit plane. The measurements were followed by an analysis of the acquired data.

Nomenclature

D = nozzle exit diameter
I_P = periodic unsteadiness intensity
I_R = random unsteadiness intensity (turbulence intensity)
I_T = total unsteadiness intensity
i_R = turbulence intensity in a time slot
L_e = excitation level
M_j = nozzle exit Mach number
R = nozzle exit radius
Re_j = nozzle exit Reynolds number
St_e = excitation Strouhal number (based on nozzle exit diameter)
T = time interval limit
t = time
U_j = nozzle exit velocity
U = velocity
u' = fluctuating velocity amplitude
X, Y, Z = coordinates
τ = time slot limit

Subscripts

A = axial
R = radial

Introduction

THE large-scale coherent structures in the mixing layer of axisymmetric, unexcited, and tone-excited jets have been investigated quite extensively in recent years.[1-12] Experimental techniques used in the cited investigations involved hot-wire anemometers and microphone probes. These techniques limited the investigations to unheated jets and very often the effect of the probe on the flow structure is in question. Thus, the use of a nonintrusive instrument such as a laser velocimeter is desirable for measurements in turbulent flows aimed at revealing the periodic behavior of the large-scale structures and quantifying the contribution of coherent large-scale oscillations to the velocity total unsteadiness level. However, the application of the laser velocimeter to these measurements is not straightforward due to the inherently random nature of the laser velocimeter signal. In the study described in this paper, data acquisition and reduction procedures have been successfully developed that enable the use of the laser velocimeter for ensemble averaging and conditional sampling.

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*Scientist. Member AIAA.

Ensemble Averaging with a Laser Velocimeter

The laser velocimeter measures flow velocity by measuring the transit time of a particle moving with the flow through the measurement volume. The random distribution of the particles in the fluid causes the velocity measurements to be taken at nonuniform time intervals. Any processing of the laser velocimeter signal using conditional sampling must account for this random nature,[13] because the randomness prevents sampling the velocity signal at prescribed time instants as is customary with analog signals. The use of an ensemble average as a time average requires an assumption of ergodicity in the phenomenon being studied.

The data reduction procedure used in this study is schematically depicted in Figs. 1 and 2.[12,14] Ensemble averaging is accomplished by synchronizing the beginning of the repetitive data acquisition intervals of the laser velocimeter with respect to the flow periodic oscillations, as shown in Fig. 1. The total time of measurement is divided into equal-time repetitive sampling intervals of length ΔT, identical with the period of the flow oscillations. As seen in Fig. 1, the limits of these intervals are marked T_n, T_{n+1}, T_{n+2}, ..., T_{n+k}. In the case of a tone-excited jet, the frequency of these limits or triggering marks is equal to the excitation frequency because the excitation and response frequencies of the jet are the same. The marks are recorded among the laser velocimeter data in a similar manner as the velocity signal.

During the postprocessing procedure, each of the repetitive sampling intervals is further subdivided into a specified number of time slots, with limits marked τ_0, τ_1, τ_2, ..., τ_j in each of the repetitive sampling intervals. While the time period of the triggering marks is controlled by the periodicity of the flow phenomena under investigation, the number of time slots in the repetitive sampling intervals is optional, is kept the same for all the sampling intervals, and can be reassigned a different value during postprocessing of the data.

The laser velocimeter data allocated to time slots within the sampling intervals can now be used to reconstruct the velocity and turbulence intensity time histories. This is accomplished by taking data over all of the sampling intervals and assigning all the acquired data points in the corresponding time slots within the single resulting file, as indicated in Fig. 2. A mean value of velocity within each time slot is then computed and this value is allocated to the center of each of the time slots, as also shown in Fig. 2. This ensemble average gives the desired velocity time history over a time interval ΔT. In fact, the velocity time history represents the changes in the flow velocity due to the organized large-scale structure, because the random, turbulent fluctuations are strongly suppressed by the averaging process if a sufficient number of averages is taken. The velocity time history is, in general, a periodic curve and can be further processed to obtain the probability distribution, variance and root mean square values, and higher-order moments. The data are also amenable to digital Fourier analysis to obtain their frequency content.

Furthermore, it is possible to compute a rms value of each of the independent data sets allocated to the individual time slots. The mean value of each of the sets is the ensemble-averaged velocity mentioned above; the rms value of the set with respect to its mean value is a measure of the fluctuation intensity associated with the random portion of the velocity signal at the time corresponding to the given phase of the periodic portion of the velocity signal. Thus, plotting the rms values for each of the time slots of the resulting time interval gives the fluctuation intensity distribution of the random portion of the velocity signal (turbulence intensity history) over the sampling interval.

The newly developed data reduction procedure was applied to the laser velocimeter measurements of the velocity field of a tone-excited free jet, described in the following sections.

Test Conditions

The jet flow facility used in this study is designed to produce low-turbulence single-stream flow.[10,11] The facility consists of

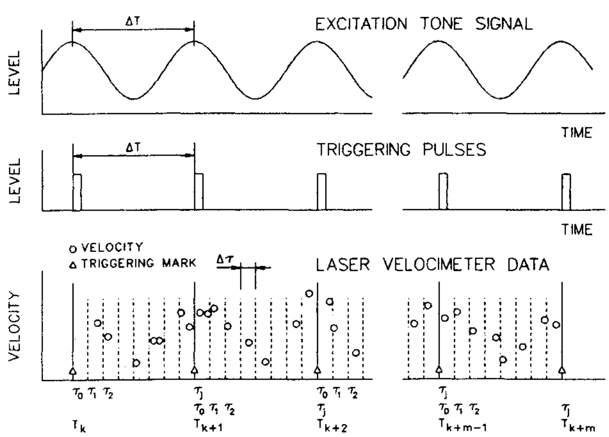

Fig. 1 Data acquisition procedure.

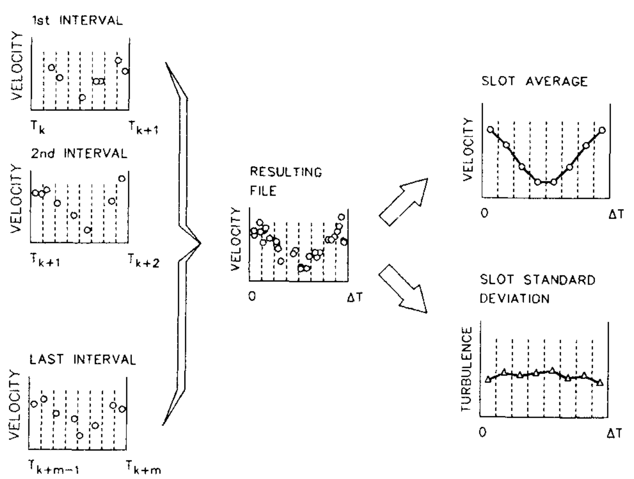

Fig. 2 Data reduction procedure.

a 50.8-mm-diam convergent nozzle connected to a plenum with a short duct 102 mm in diameter. The area contraction ratio of the plenum/nozzle is 25. The short duct is a part of the source section for the upstream acoustic excitation.

The source section utilizes four electroacoustic 100 W Altec drivers, spaced uniformly around the source section duct. The drivers are connected to the short duct just upstream of the test nozzle using connecting tubes 25.4 mm in diameter. The voltage and phase of the driving signals of the four drivers were adjusted to generate the plane wave mode acoustic excitation at the test nozzle exit plane. The electronic driving signal of one of the drivers served as a triggering signal for the ensemble averaging of the laser velocimeter data.

The laser velocimeter used in this study is an advanced counter-type, two-color, four-channel instrument developed at Lockheed-Georgia Company. The velocimeter for this particular measurement was arranged in a forward-scatter mode with an off-axis location of the collecting optics at an angle of 30 deg. The length of the measurement volume was 1 mm and the diameter was 0.15 mm. The total laser power used was 3.5 W and the total light power measured in the measurement volume was 1.1 W. Alumina powder particles, 1 μm in diameter, mixed with a fused silica flowing agent (Cab-O-Sil), were used to seed the flow. Further details of the test facility and the laser velocimeter are given in Refs. 10 and 11.

All experiments were run either with a tone-excited or unexcited free jet at two jet exit Mach numbers, $M_j = 0.3$ and 0.9. However, only the results of experiments at $M_j = 0.3$ are reported in this paper because, at this Mach number and the given excitation conditions described below, the large-scale structure has been found to be well defined. The total temperature of the flow was identical to the ambient temperature. The level of excitation measured at the nozzle exit plane was maintained at 138 ± 1 dB (relative to 2×10^{-5} Pa). The frequency of excitation for $M_j = 0.3$ was chosen to be 991 Hz; thus, the value of the excitation Strouhal number was $St_e = 0.5$.

The experiments started with the measurement of mean velocity and total unsteadiness distributions along the jet centerline in unexcited and tone-excited jets. Then, the ensemble-averaging procedure was applied to measurements performed in that region of the free-jet flowfield where the most significant effects of the upstream acoustic excitation were observed.

Global Behavior of the Tone-Excited Jet

The basic differences between unexcited and tone-excited jets, as far as centerline distributions of the axial component of the mean velocity and turbulence intensity (velocity unsteadiness intensity) are concerned, are shown in Figs. 3 and

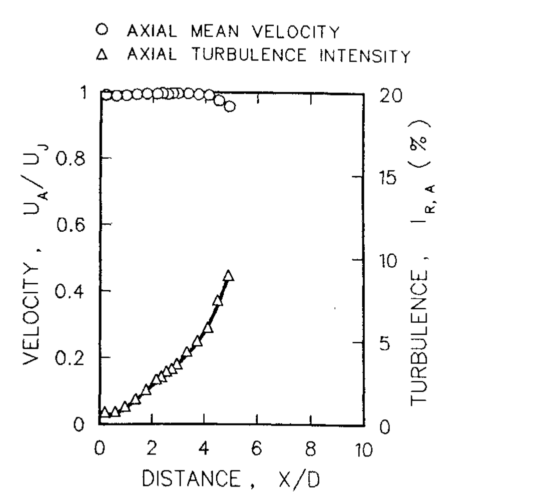

Fig. 3 Centerline distributions for an unexcited jet ($M_j = 0.3$, $U_j = 100.8$ m·s^{-1}).

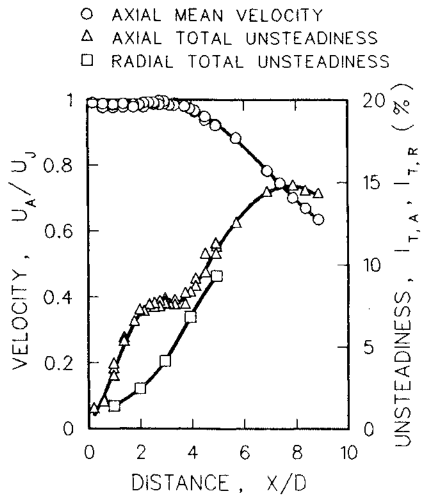

Fig. 4 Centerline distributions for a tone excited jet ($M_j = 0.3$, $U_j = 101.3$ m·s^{-1}, $St_e = 0.5$, $L_e = 139$ dB).

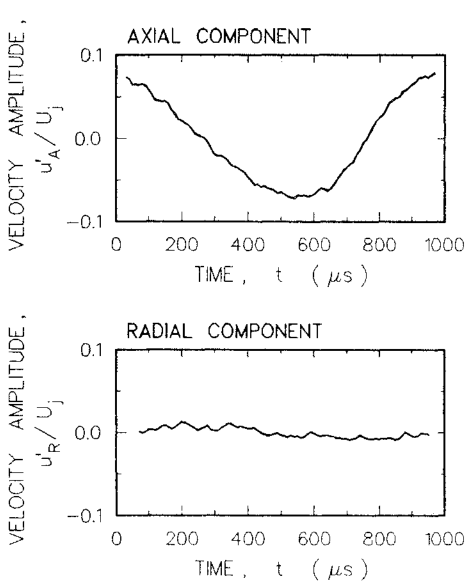

Fig. 5 Ensemble-averaged velocity histories at the jet centerline ($X/D = 2.95$, $M_j = 0.3$, $U_j = 102.0$ m·s^{-1}, $St_e = 0.5$, $L_e = 139$ dB).

4. For $M_j = 0.3$, the potential core of the unexcited jet extends to $X/D = 4$ (Fig. 3), after which the mean velocity starts to decrease. The turbulence intensity (Fig. 3) steadily increases over the whole measured range up to $X/D = 5$. In the case of the tone-excited jet in Fig. 4, however, the length of the potential core was reduced approximately to $X/D = 3.5$. Furthermore, the velocity in the potential core was no longer constant, but had a slightly lower level with an obvious local minimum in the region $X/D = 1.5$-2.0. Similar results have been reported in the literature.[1,10-12]

In the case of the tone-excited jet, the velocity unsteadiness intensity shows significant changes in the potential core (Fig. 4) in comparison with the turbulence intensity distribution of the unexcited jet. The unsteadiness intensity grows at a substantially higher rate, reaches a distinct local maximum at $X/D = 3$ followed by a slight decrease, and then increases again to the second maximum. The first "hump" in the unsteadiness intensity distribution is the contribution of the growing, enhanced large-scale structure to the total unsteadiness intensity level as explained by Crow and Champagne[1] and Ahuja et al.[10,11] In addition to the "hump" within the potential core, the unsteadiness intensity is higher in the whole measured range in comparison with the turbulence intensity of the unexcited jet. The radial component of the velocity unsteadiness, however, does not show any peculiarity at $X/D = 3$, as seen in Fig. 4.

Thus, in the case of the tone-excited jet, it appears that the resulting level of the velocity total unsteadiness combines the contributions of both velocity periodic fluctuations (large-scale structure) and velocity random fluctuations (turbulence level). As shown in the next section, the ensemble-averaging method can separate these independent contributions to the velocity total unsteadiness level.

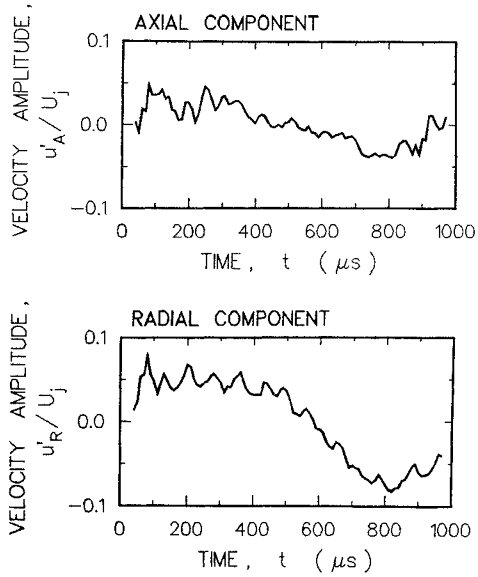

Fig. 6 Ensemble-averaged velocity histories at the jet lipline ($X/D = 2.95$, $M_j = 0.3$, $U_j = 102.1$ m·s^{-1}, $St_e = 0.5$, $L_e = 139$ dB).

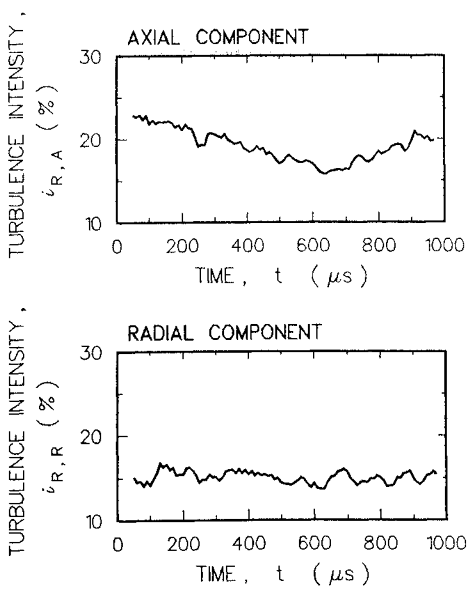

Fig. 7 Ensemble-averaged turbulence intensity histories at the jet lipline ($X/D = 2.95$, $M_j = 0.3$, $U_j = 102.1$ m·s^{-1}, $St_e = 0.5$, $L_e = 139$ dB).

Velocity Time Histories

The application of the ensemble-averaging technique reveals periodic fluctuations of both components of the instantaneous velocity for a tone-excited jet. The amplitude and phase of these periodic fluctuations depend very strongly on the location of the measurement point in the jet. The time histories of the measured instantaneous velocity components, together

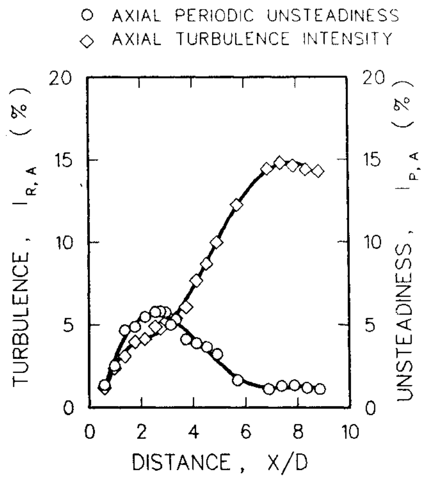

Fig. 8 Centerline distributions for a tone excited jet ($M_j = 0.3$, $U_j = 101.6\ \mathrm{m \cdot s^{-1}}$, $St_e = 0.5$, $L_e = 138$ dB).

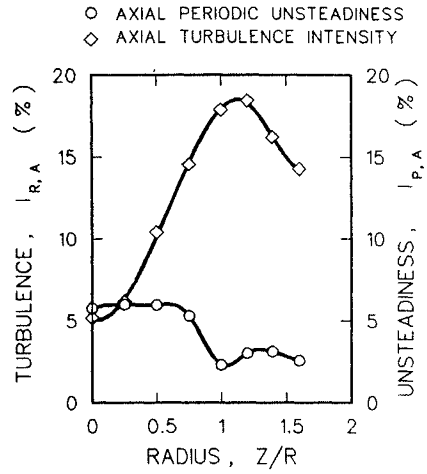

Fig. 9 Radial profiles for a tone-excited jet, axial velocity component ($X/D = 2.95$, $M_j = 0.3$, $U_j = 101.4\ \mathrm{m \cdot s^{-1}}$, $St_e = 0.5$, $L_e = 138$ dB).

with their phases relative to the excitation signal, are shown in Fig. 5 for the centerline location and in Fig. 6 for the lipline location. From Fig. 5, the maximum amplitude of the axial component of the velocity measured at the centerline is about an order of magnitude higher than the amplitude of the radial component. This explains why there is no detectable "hump" on the centerline distribution of the radial component of turbulence intensity in Fig. 4. The fluctuations of the radial velocity component with respect to the axial velocity component are shifted approximately 90 deg. Similar comparisons for the lipline location are made in Fig. 6. The amplitude of the radial fluctuations is approximately twice that of the axial ones. The phase of both components on the lipline is about the same.

Time histories of both components of the velocity random fluctuation intensity (turbulence intensity) for the lipline location at $X/D = 2.95$ are shown in Fig. 7. The level of the radial component of the turbulence intensity during the period of flow fluctuations is relatively constant, while the axial component shows periodic changes in level during a period of the flow fluctuations. These periodic changes of the axial component of turbulence intensity are probably caused by the passages of the vortex cores through the measurement volume.

Velocity Periodic and Velocity Random Unsteadiness

The unsteadiness intensities are computed from velocity time histories. The intensities are normalized by the jet exit velocity. The intensity of the velocity periodic fluctuations (periodic unsteadiness intensity) is computed as a standard deviation of the velocity periodic fluctuation amplitude from its mean value. The intensity of the velocity random fluctuations (turbulence intensity) is computed as a mean value of the turbulence intensity time history over one period of the flow oscillations. Now, it is possible to plot separately the periodic unsteadiness intensity caused by the large-scale structure and the turbulence intensity level.

The centerline distributions of the periodic unsteadiness intensity and turbulence intensity for the axial velocity component are shown in Fig. 8. The "hump" present in the total unsteadiness level distribution at $X/D = 3$ (Fig. 4) is significantly reduced in the distribution of the turbulence intensity. The periodic unsteadiness intensity shows a distinct maximum at $X/D = 3$. This clearly indicates that the local maximum of the total unsteadiness level of a tone-excited jet, in the region of the end of the jet potential core, is due to the contribution of the developed organized large-scale structure. However, the turbulence intensity has also increased somewhat in this range due to the jet excitation.

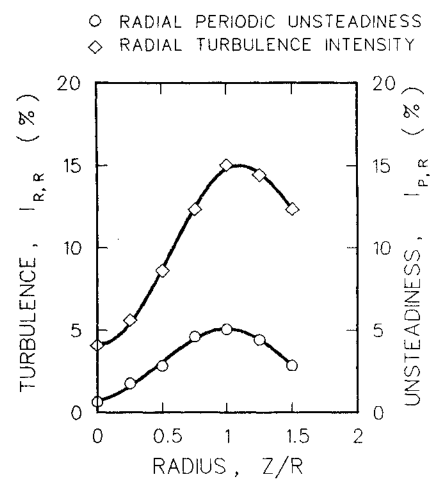

Fig. 10 Radial profiles for a tone-excited jet, radial velocity component ($X/D = 2.95$, $M_j = 0.3$, $U_j = 102.0\ \mathrm{m \cdot s^{-1}}$, $St_e = 0.5$, $L_e = 139$ dB).

The radial distributions of the periodic unsteadiness intensity and turbulence intensity for both velocity components at $X/D = 2.95$ are plotted in Figs. 9 and 10. For both velocity components, the distributions of turbulence intensities strongly resemble the similar turbulence intensity distributions of an unexcited jet. However, the periodic unsteadiness behaves differently for both the axial and radial components. While the radial distribution of the periodic unsteadiness intensity for the axial component is unchanged across the potential core with a distinct minimum at the lipline (Fig. 9, $Z/R = 1$), the corresponding distribution for the radial component shows a minimum at the centerline with a significant increase in the region of the shear layer around the lipline (Fig. 10). Thus, for the excited jet compared to the axial component, the radial component of the total velocity unsteadiness appears to be enhanced more strongly in the shear layer. Therefore, the difference between the axial and radial components of the total unsteadiness intensity in the shear layer of a tone-excited jet is less than that for an unexcited jet. The increased radial unsteadiness intensity level increases the spreading rate of the tone-excited jet plume and the rate of mixing with the surrounding ambient air.

Conclusions

The following two principal conclusions result from the present investigation:

1) A laser velocimeter with ensemble averaging was successfully used for the two-component velocity measurement of the organized, large-scale structure of a tone-excited jet.

2) The decomposition of a velocity total unsteadiness level into a velocity periodic unsteadiness level associated with the large-scale structure and a turbulence level was demonstrated.

Acknowledgments

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