Time-Resolved Two-Dimensional Concentration Measurements in an Acoustically Driven Flow

Marshall B. Long,* Huey-Ming Tzeng,† and Dominique Fourguette‡
Yale University, New Haven, Connecticut

A nonintrusive optical technique for making simultaneous time-resolved concentration measurements at 10,000 points within a plane intersecting an acoustically forced axisymmetric jet is described. The technique, which involves the pulsing of a laser synchronously with an acoustic perturbation, is similar to a method developed for two-dimensional mapping of concentrations using a single laser pulse. Different scattering mechanisms, including Lorenz/Mie scattering and fluorescence, have been used for mapping the concentration distributions of large-scale structures in forced axisymmetric jets.

Introduction

THE importance of organized large-scale structures in turbulent flows has become widely recognized. To study these structures, current experiments are making greater use of conditional sampling, multipoint measurement techniques, and flow visualization. However, in many flow situations, it is still difficult to obtain detailed quantitative information on the spatial characteristics of the structures, and a need remains for better nonintrusive diagnostics for mapping the structures.

Several investigators[1-6] have recently made use of the fact that it is possible to "force" the naturally occurring instabilities in a jet flow. Information on the large-scale structures can be obtained by making time-resolved measurements at a specific interval after the instabilities have been triggered since, in effect, the phase information of the flow is preserved. For example, Perry and Lim[1] performed flow visualization experiments in which a stroboscopic light was used to illuminate a smoke-laden flow in phase with the forcing mechanism. Because each light pulse illuminated events with a similar origin, the resulting patterns appeared to be stationary. In addition, it was possible to trigger the light at successively later times with respect to the forcing and thereby obtain the equivalent of a time history of the structures in the flow. In their work, Perry and Lim forced the jet by physically vibrating the nozzle. In other studies, acoustic excitations[4] have been used to trigger instabilities in the flow.

In an effort to provide new data on these structures, new optical techniques have been developed that allow the instantaneous mapping of the gas concentrations within a plane intersecting a turbulent flow. These techniques, which have been reported elsewhere,[7-9] can be easily adapted to make time-resolved measurements in phase with forced flow systems. The resulting data from the accumulation of many such time-resolved measurements have the advantage of improved signal-to-noise ratio and, in several cases, it is possible to use much weaker scattering mechanisms that would not provide enough signal otherwise.

Experimental Approach

The experimental configuration used for making time-resolved concentration measurements in phase with a forced flow is shown schematically in Fig. 1. For the results to be reported here, several different axisymmetric nozzles with diameter $d = 4$ mm were used. The nozzle gas could be seeded with either aerosol particles for the Lorenz/Mie experiments or fluorescing molecules for the fluorescence work. The nozzles used were of conventional design and both flowmeters and a differential manometer were used for monitoring the gas flow rates.

A thin sheet of illumination was formed by first focusing an argon-ion laser (488 and 514.5 nm at 2 W) with a spherical lens and then diverging the beam in one direction with a cylindrical lens. The resulting illumination sheet, roughly 200-μm thick, was directed through the center of the jet flow, parallel to the jet axis. In order to pulse the laser radiation, an acousto-optic modulator was used as a switch. The modulator was triggered by the same function generator that drove the loudspeaker so that the laser was pulsed on for a short time (10 μs) in phase with the acoustic forcing. The scattered light emerging from the sheet of illumination was imaged onto a computer-controlled, low-light-level television camera (PAR OMA-2). The computer controls the camera scan and the image is stored in the computer as a 100×100 array.

Two different sources of acoustic excitation were used in these experiments. One source was simply a loudspeaker placed ~30 cm from the jet. In order to obtain a more localized form of acoustic excitation four small loudspeakers with diameters of 4.3 cm were used for some experiments. Each loudspeaker was connected to a converging section with an exit diameter of 3.0 mm which provided an effective "point source" of acoustic excitation. These point sources were positioned so that the end of the converging section was two jet diameters from the jet axis. In addition, translation stages allowed them to be placed at various locations along the jet axis near the nozzle. It was determined experimentally that the presence of the converging tubes did not alter the flow when the acoustic perturbation was not present.

Lorenz/Mie Scattering Results

The light scattering mechanism that provides the largest scattered light intensity for these experiments is Lorenz/Mie scattering (i.e., elastic scattering from submicron-sized particles). Using this scattering mechanism, we have shown that it is possible to obtain a complete gas concentration mapping at 10,000 points within a plane in a single laser pulse (10 μs).[7] The dominant noise source in this experiment, however, is the so-called marker-shot noise associated with the fact that, in each illuminated volume, there are only a finite number of particles. This noise can become quite large if the volume observed is small or if the flow cannot be seeded sufficiently heavily. However, by doing the same type of experiment in the forced jet, the marker-shot noise present in a single shot can be averaged out by the addition of many single-shot events and the resulting conditionally averaged distribution has considerably less marker-shot noise. In addition, since signals are now very large, the laser sheet can be expanded and a larger region of the jet can be observed.

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*Assistant Professor, Applied Mechanics, and Center for Laser Diagnostics.

†Graduate Student, Applied Mechanics.

‡Graduate Student, Applied Physics.

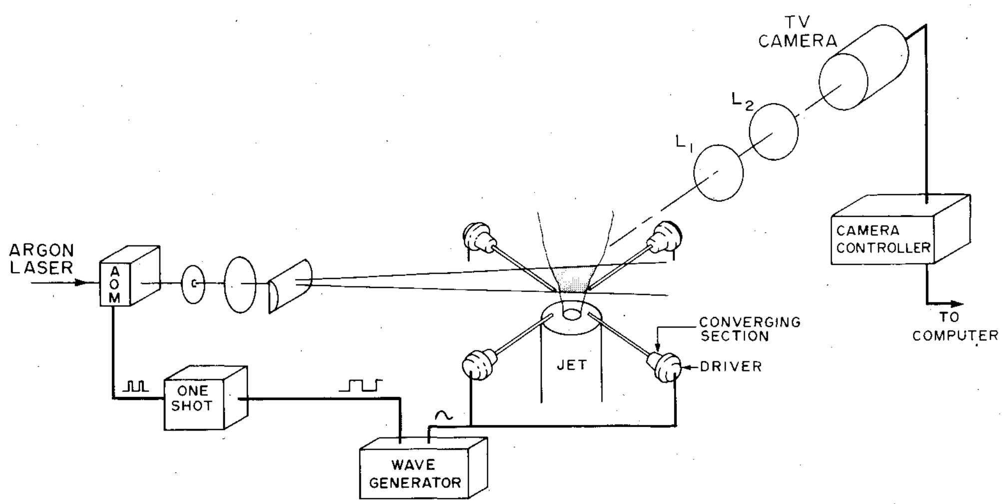

Fig. 1 Experimental configuration used for making two-dimensional, time-resolved gas concentration measurements in phase with an acoustically driven flow. A laser is pulsed in phase with the acoustic disturbance by an acousto-optic modulator (AOM). The beam is formed into a thin sheet and the scattered light from within the illuminated plane is imaged onto a low-light-level television camera.

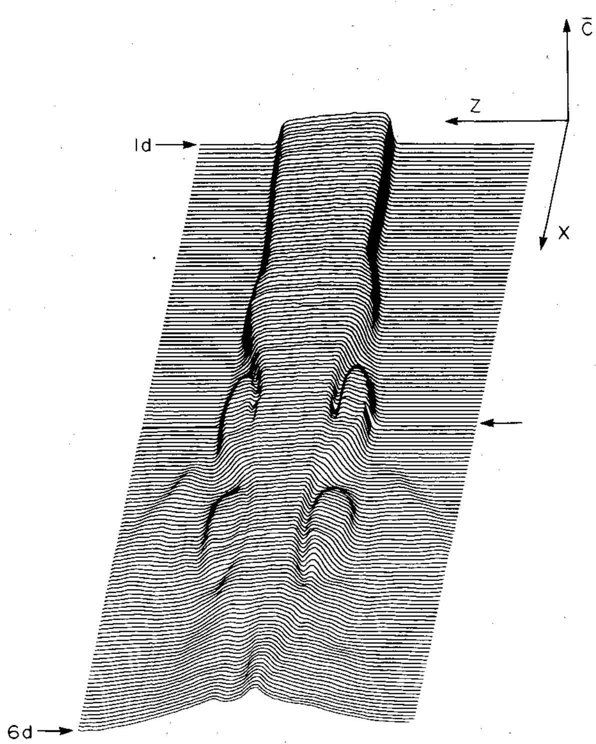

Fig. 2 Composite of two regions of gas concentration obtained in a forced flow by Lorenz/Mie scattering. The acoustic perturbation was generated by an array of four acoustic point sources located at 3.3*d* downstream, as indicated by an arrow in the figure.

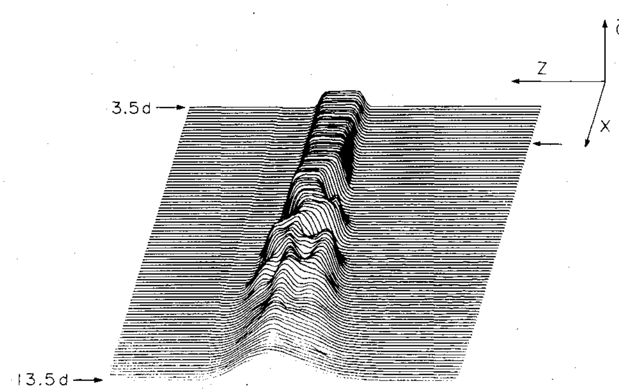

Fig. 3 Gas concentration distribution in a forced flow obtained by Lorenz/Mie scattering. For this data, two acoustic sources were used with one located at the nozzle exit and the other at 4.0*d* downstream, as indicated by the arrow.

Figure 2 shows results obtained using the localized acoustic forcing setup. Because the flow appears essentially stationary when illuminated in phase with the acoustic forcing, it is possible to combine many measurements with different locations of the illumination sheet. The figure, which is actually a composite of two sets of data, shows the region from 1.0 to 6.5 jet diameters downstream. The four acoustic point sources were located at 3.3 jet diameters downstream, as indicated in the figure. The forcing frequency was 3.8 kHz and the Reynolds number (based on nozzle diameter) was 2300. It is clear that even though this is the average of several thousand "instantaneous" shots, the essential features of the coherent structures are preserved. All data shown here have been corrected for the nonzero background and nonuniform response characteristics of the television camera detection system. This two-step process, which is the same as that used previously in the single-shot experiments, has been described in detail elsewhere.[7,9]

In Fig. 3, only two acoustic sources were used, with one located at the nozzle exit and the other at 4.0 diameters downstream. For this result, a forcing frequency of 0.5 kHz was used and the Reynolds number was 1950. Because the signals from the elastic scattering were quite strong, the illumination sheet was expanded to a width of 10 jet diameters covering the region from 3.5*d* to 13.5*d*. The pattern is clearly different than for the symmetric forcing case shown in Fig. 2. The structures in the jet now develop asymmetrically with the first clearly visible structures appearing downstream of the acoustic source at 4.0*d*. A more complete investigation of the nature of the interaction of the localized acoustic excitation and the unstable shear layer is currently under way.

Another example of the ability of the Lorenz/Mie technique to provide quantitative data in a forced flow is shown in Fig. 4. In the figure, a sequence of six sets of data from the same flow are shown. For each, two constant concentration contours are plotted, one at 40% and another at 60% of the maximum concentration. Successive data sets, showing the region from 3.1 to 6.8 jet diameters downstream, were taken at slightly longer phase delays with respect to the forcing acoustic excitation, yielding the effective time sequence shown in the figure. Forcing at a frequency of 2.9 kHz was provided by the four localized acoustic sources located at 4.7*d*. From this type of data, quantities such as the convection velocity of the lobed structures can be calculated. To do this, the movement of common features (e.g., the

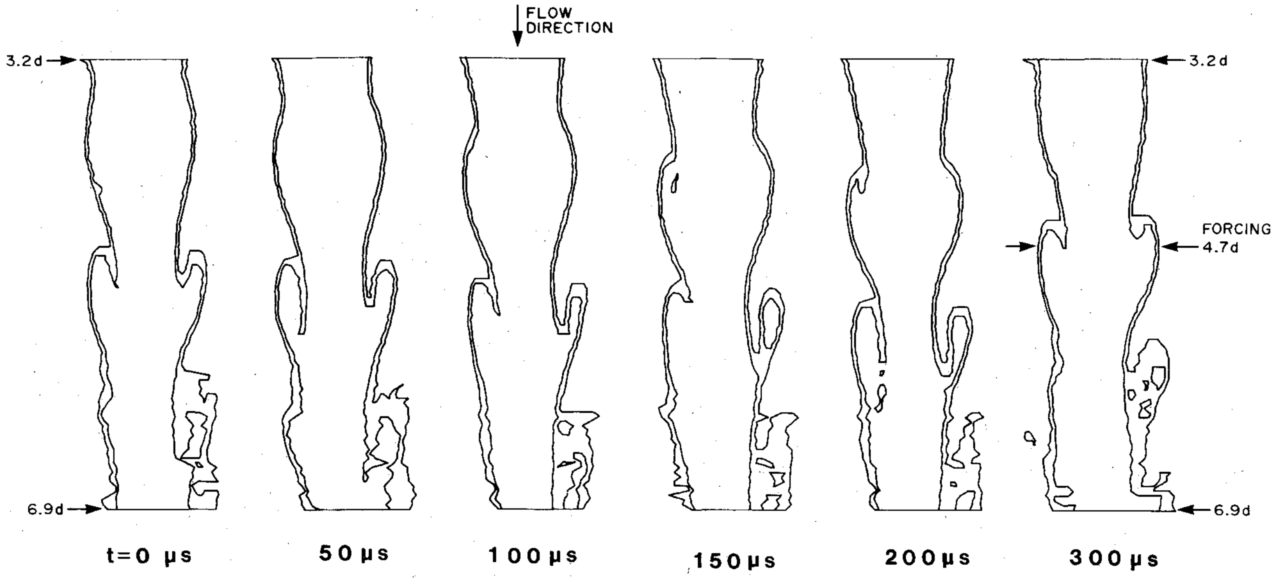

Fig. 4 A sequence of nozzle gas concentration measurements made at successively larger phase delays with respect to the acoustic forcing. For each measurement, constant concentration contours are shown for 40 and 60% of the maximum gas concentration.

location of a particular structure) is noted and the displacement of the feature measured. The time required for the displacement is obtained from knowledge of the forcing frequency and, thus, the convection velocity can be calculated. Using this scheme, the convection velocity of structures shown in Fig. 4 was determined to be 45% of the mean nozzle exit velocity which was 14.4 m/s.

Fluorescence Measurements

Another means of measuring the gas concentration distribution is to tag one of the flow components with a fluorescing molecular species.[10-16] This approach has several potential advantages over seeding the flow with aerosol particles. 1) With a molecular tag, there is no longer concern about the ability of a particulate to accurately follow the acceleration of the flow. 2) Since the motion of the gas molecules themselves is monitored, molecular diffusion effects will be detectable; this is clearly not possible with an aerosol tag. 3) The detected signal in the fluorescence case is at a different wavelength than the incident laser radiation. Thus, an optical filter can be used that passes only a narrow band of wavelengths corresponding to the fluorescence radiation and not the incoming laser light. This makes measurements of the concentration distribution possible in flow systems, such as boundary-layer flows, in which there may be significant specular reflection, stray light, or particulates.

Iodine vapor is a convenient molecular tag for use in the room temperature, low-velocity flows studied here. The vapor pressure of solid iodine is 250 mTorr so that, by simply passing the room temperature gas through a chamber filled with iodine crystals, a sufficient iodine seeding concentration can be attained ($\sim 10^{16}$ molecules/cm^3). In addition, there is a coincidence of the 514.5 nm emission of an argon-ion laser with several optical transitions in iodine, thus providing a convenient means of exciting the iodine fluorescence.

The scattered light obtained from a single shot in the fluorescence case is about a factor of 10^3 weaker than that obtained with Lorenz/Mie scattering. Therefore, a high-power pulsed laser source would be required to obtain single-shot data. In the forced flow case, however, the relatively weak time-resolved signal can simply be integrated on the television camera detector. The noise in data obtained in this way is primarily due to camera-readout noise and photon-shot noise (rather than marker-shot noise). This can be reduced by simply accumulating a large number of the time-resolved measurements.

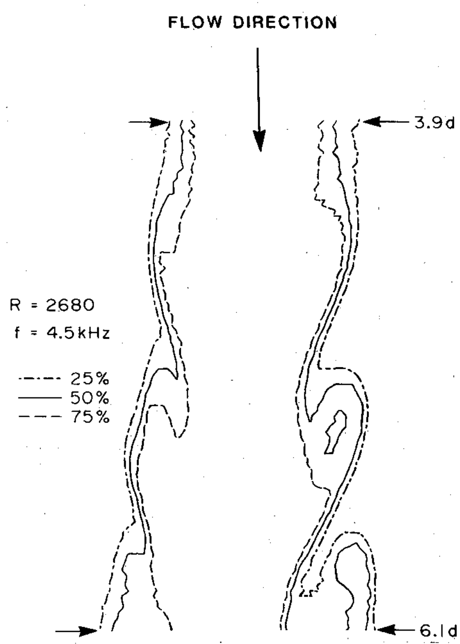

Fig. 5 Constant nozzle gas concentration contours in a forced jet measured using iodine fluorescence. To obtain sufficient signal, approximately 3600 individual "instantaneous" concentration distributions were accumulated on the face of the television camera. Contours are shown for 25, 50, and 75% of the maximum nozzle gas concentration.

The experimental configuration used for the fluorescence work is basically the same as that shown in Fig. 1, except that color filters which pass only the fluorescence radiation were added to the collection optics. Also, the nozzle used had an internal protective glass covering to prevent corrosion of the nozzle by the iodine. An experimental result for the forced jet seeded with iodine is shown in Fig. 5 for a Reynolds number (based on nozzle diameter) of 2680. In the figure, constant concentration contours are shown for 25, 50, and 75% of the maximum centerline concentration. In this case, a single loudspeaker was placed near the jet and driven sinusoidally at a frequency of 4.5 kHz. To obtain sufficient signal, the fluorescence radiation from many laser pulses was integrated on the television camera for a period of 0.8 s. Thus, the data in the figure are actually the result of averaging approximately 3600 individual concentration contours.

Conclusion

The optical techniques developed previously for obtaining instantaneous two-dimensional gas concentration measurements have been adapted to make time-resolved measurements in phase with forced flows, and the results obtained in this manner have several advantages. Since many similar events can be accumulated, the signal-to-noise ratio is significantly improved, compared to single-pulse measurements. It, therefore, is possible to observe a larger region of the jet, either by expanding the illumination sheet or by combining data sets taken in different regions of the flow. Another significant advantage is the ability to make use of much weaker inelastic molecular scattering mechanisms (such as fluorescence) for measuring the gas concentration. With these scattering mechanisms, the molecules of the flow are measured directly and problems related to particulates in the flow are avoided.

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