

## A technique for real-time visualization of flow structure in high-speed flows

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A newly developed MHz rate imaging system that provides real-time flow visualization is described. The technique utilizes a custom-built Nd:YAG pulse burst laser and an ultra high-speed digital camera and is capable of capturing 17 images over 150 microseconds. The system was used to visualize a Mach 1.3 ( $M_c=0.6$ ) axisymmetric jet. Sample results indicate the potential of the technique to provide detailed information on the dynamic characteristics of large-scale structures. A two-dimensional cross-correlation technique was used to calculate the convective velocity of large-scale structures. Present results generally agree with the findings of earlier investigations that indicate a significant deviation of the convective velocity from theoretical predictions. © 2002 American Institute of Physics. [DOI: 10.1063/1.1503802]

Over the last few decades, a large number of researchers have used pulsed lasers to visualize large-scale turbulence structures within high-speed flows. These flow visualization systems typically consist of lasers with low repetition rates ( $<100$  Hz) and high pulse energies ( $>100$  mJ/pulse) coupled with digital cameras with large format CCD chips and high receptivity to light. These techniques form the basis for much of our understanding of compressible flows, which are generally characterized by the convective Mach number,  $M_c$ . It has been found that for relatively low levels of compressibility ( $M_c < 0.5$ ) the structures within the shear layer generally are two dimensional, with large organized spanwise rollers. As the compressibility level is increased ( $M_c > 0.5$ ), these large-scale structures become less organized and much more three dimensional.<sup>1–5</sup> This inherent change in turbulence structure has a profound effect on the flow development, including a significant reduction in the mixing layer growth rate. Development of a more detailed understanding of the dynamic behavior of the compressible mixing layer has been inhibited by the lack of temporal resolution associated with typical flow visualization techniques. In the past few years, however, advances in both laser and camera technology have allowed for the acquisition of a series of real-time images. These advances have the potential to greatly increase the overall understanding of high-speed compressible flows. This article describes the development of a real-time flow visualization technique and demonstrates its potential by applying it to a Mach 1.3 axisymmetric jet.

The real-time technique utilizes a custom-built pulse burst laser and an ultrahigh framing rate digital camera to acquire 17 flow visualization images over a span of 150 microseconds. The laser, illustrated schematically in Fig. 1, is a second generation system based on that described previously by Lempert *et al.*,<sup>6,7</sup> Wu *et al.*,<sup>8</sup> and Thurow *et al.*<sup>9</sup> A continuous wave Nd:YAG ring laser serves as the primary oscillator, the output of which is preamplified in a double-pass,

flashlamp-pumped, pulsed amplifier. The resulting, approximately 150 microsecond duration pulse is formed into a “burst” train using a dual Pockel Cell “slicer.” The train can have a variable number of pulses, between 1 and 99, with interpulse timing varying between 1 and 100 microseconds. The individual pulse durations are 10 ns. For the experiments to be described, a typical burst consisted of 17 pulses (limited by the camera), with 10 ns duration and 2–10 microsecond interpulse timing. The pulse train is further amplified by a pair of additional double-pass amplification stages and a single-pass, double-flashlamp, amplification stage. It is then converted to the second harmonic wavelength of 0.532 microns (“green”) using a KTP crystal.

Figure 2 shows a typical burst train with an interpulse timing of 5 microseconds. The average output energy per individual pulse at 0.532 microns is approximately 7 mJ. Typical pulse energies vary between 2 and 15 mJ/pulse depending on the length of time between pulses. Longer separations between pulses correlate to higher pulse energies with the entire burst limited to the 150 microsecond amplification envelope. The timing of the four amplifiers is varied relative to one another in order to distribute the power evenly over the entire burst. The overall burst process has a repetition rate of 10 Hz.

The ultrahigh-speed framing camera was manufactured by Silicon Mountain Design (SMD) (now a subsidiary of Dalsa, Inc.). The camera can acquire 17 images at a variable rate as fast as 1 MHz. Each image in the sequence has a resolution of  $245 \times 245$  pixels. The camera is based on a large format ( $1024 \times 1024$ ) 12 bit CCD chip in which 16 out of 17 pixels are hidden by a mask. By appropriate shifting of charge, individual images are initially stored in pixel locations under the mask. The net fill factor, limited primarily by the mask, is less than 3%, resulting in an effective pixel active dimension of  $\sim 10$  microns. Furthermore, the quantum efficiency of the CCD chip is  $\sim 10\%$ , so that the camera sensitivity is only about 1–5% of the sensitivity of a typical research grade CCD camera. After accumulation of all the images, a PC reads the output as one large image, containing

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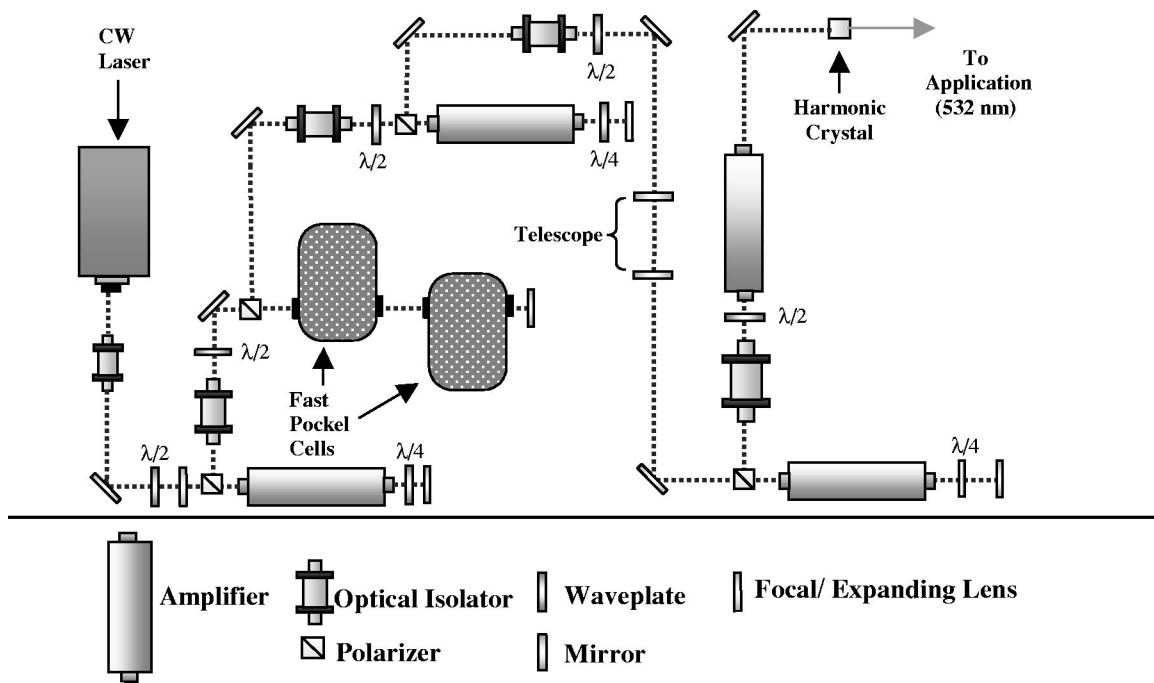


FIG. 1. Schematic of pulse burst laser system.

all 17 frames. The output signal is transferred to a computer via four parallel data ports, each comprising a quarter size column of the image.

The experiments were conducted at The Ohio State University's Gas Dynamics and Turbulence Laboratory (GDTL). The jet facility at GDTL has been described in detail elsewhere.<sup>10,11</sup> The jet nozzle was designed using the method of characteristics and has a 25.4 mm (1 inch) exit diameter and a measured Mach number of 1.28 ( $M_c = 0.59$ ). Pressure to the stagnation chamber is controlled manually through the actuation of a Fisher control valve and can be maintained at constant pressure within 0.3 psi. Pressure was set for ideally expanded flow.

The pulse burst laser beam was formed into a sheet to illuminate either the streamwise or cross-stream planes of the jet's mixing layer. The flow was naturally seeded using the product formation technique, whereby moisture from warm, moist, ambient air condenses in the mixing layer when the ambient air is mixed with cold, dry air from the jet. This

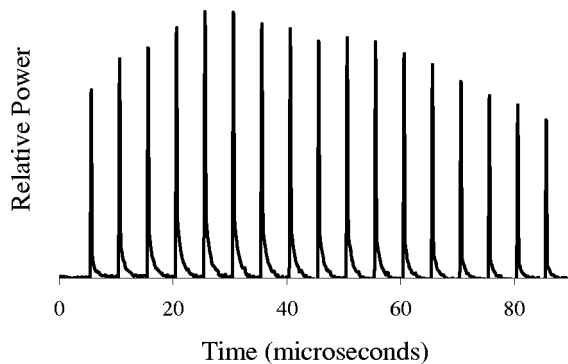


FIG. 2. Typical burst train for MHz pulse burst laser; pulses are separated by 5 microseconds each and contain approximately 7 mJ each.

technique produces a fine mist of water particles with diameters on the order of 50 nm, which are small enough to follow the flow.<sup>12</sup> For the streamwise images, the interpulse timing of the laser was set at either 5 or 10 microseconds. Generally, the sheet was formed to cover a streamwise length of approximately 4 jet diameters and the camera was placed  $\sim 1$  meter away, oriented orthogonal to the sheet. For the cross-stream images, the interpulse timing was set to either 2 or 4 microseconds due to the high speed and rapid development of the flow passing through the laser sheet. A nominal 4–5.6 f/number, 220–400 mm zoom lens was employed, with a  $\sim 8:1$  image magnification.

Each sequence of images was processed using MATLAB software. A background image was subtracted from each individual frame. Intensity values were then scaled so that the minimum and maximum values would range between 0 and 1, respectively. Due to the Gaussian nature of the laser sheet, each image was corrected on a shot-to-shot basis for nonuniformity of the laser sheet's intensity. The 17 images were then sequenced together and saved in AVI movie format for analysis.

Figure 3 is a sequence of images obtained using the technique applied to the Mach 1.3 ( $M_c = 0.6$ ) axisymmetric jet. The figure contains only four streamwise images taken from a complete set of 17. Flow is from left-to-right and only the mixing layer is visualized. Images in the figure are separated in time by 25 microseconds; in the full set of 17 images, there is 5 microseconds separation between images. The most striking dynamic feature depicted in these four images is the roll up of a large-scale structure in the bottom half of the mixing layer. The rectangle in the first image indicates a region of the mixing layer that is wavy in appearance. In the following images, one can follow the roll up process as a large-scale structure is formed. This structure is clearly seen

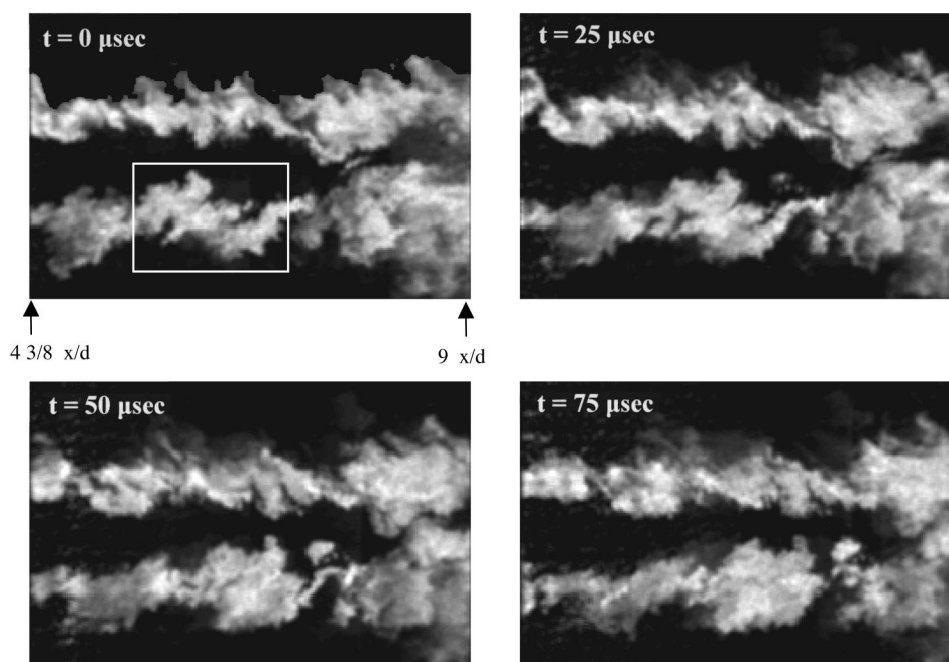


FIG. 3. Four images (out of a sequence of 17) of a Mach 1.3 axisymmetric jet. Only the mixing layer is visualized.

in the last image and consists of the familiar core preceded and followed by braid regions. It is emphasized that Fig. 3 only depicts four frames out of a total of 17. Viewing the full sequence of 17 images can reveal more details about the development of the flow than possible with double-pulse flow visualizations. For example, the sequence of Fig. 3 also displays the emergence of fluid into the field of view from out of the plane of the laser sheet. This can be seen immediately downstream of the structure just described (particularly evident in the third and fourth frames above the braid region) and helps illustrate the three-dimensional nature of this flow. The three-dimensional nature of the flow is vividly shown in cross-stream images not presented here. Through the course of viewing hundreds of movies, many other structure events such as tilting, stretching, tearing, and pairing have been observed. Some of these events can be seen in Fig. 3, but are more evident in other image sequences not shown here. An example of the tilting and stretching mechanisms can be seen in the bottom half of the mixing layer of Fig. 3. Immediately upstream of the rectangle in the first frame, one can identify a large-scale structure. Following this structure through the remaining frames, one can see the structure tilt and stretch in the direction of the shear.

The theoretical convective Mach number of the Mach 1.3 jet is 0.6 and thus the mixing layer is expected to exhibit both compressible and incompressible characteristics, as noted in other related works dealing with the effects of compressibility.<sup>1–5</sup> In general, similar observations were made using this technique. Characteristics of the compressible mixing layer were evident by the lack of any clear organization of large-scale structures and the short lifetimes of identified structures. Large-scale structures could be clearly observed (as is the case in Fig. 3), however, and on occasion would appear in an organized fashion as a train of structures

interconnected by the braid regions. Thus, the mixing layer is seen to be in a transition state between incompressible and compressible flow and features of both can be identified. This was further demonstrated by cross-stream movies (not shown here), which show the mixing layer to be very three-dimensional and influenced by the presence of streamwise vortices.

In addition to the qualitative features observed in the movies, convective velocity calculations were made using a two-dimensional cross-correlation technique to track individual structures as they convect downstream. This procedure has been employed by several researchers (e.g., Refs. 4 and 5) on image pairs obtained using either two lasers or a single double-pulsed laser. In these studies, a structure is identified in the first image (either manually or automated) and a template is made from the intensity information in the region of the structure. This template is then scanned across the second image and cross correlated. The location where the cross-correlation coefficient is the maximum is then taken as the time-delayed location of the structure. The convective velocity is simply

$$U_c = \frac{\Delta x}{\Delta t}, \quad (1)$$

where  $\Delta x$  is the displacement of the structure in time,  $\Delta t$ .

The full details of the technique applied here are presented in Thurow.<sup>13</sup> Figure 4 is a histogram of the convective velocity using both an automated and manual method of calculation. The histogram for the automated case is based on 150 image sequences with velocity measurements made in both the upper and lower halves of the mixing layer. 275 out of 300 possible measurements are presented with the remaining measurements rejected (i.e., low correlation level, etc.).

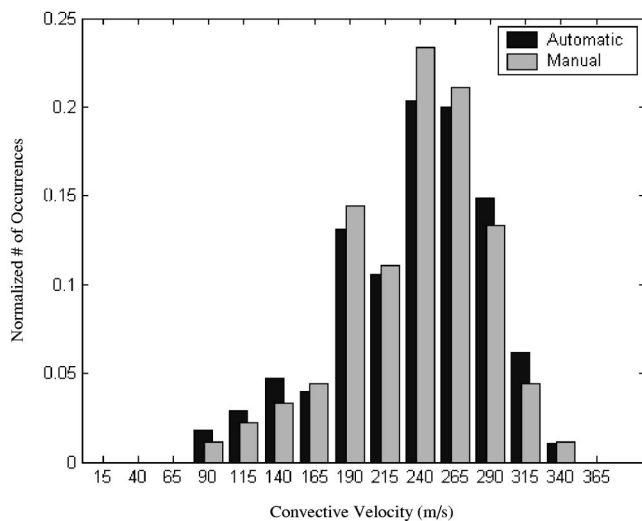


FIG. 4. Histogram of convective velocity results using the manual and the automated cross-correlation methods.

The manual method consists of 87 measurements and is a confirmation of the effectiveness of the fully automated technique. The average convective velocity is 260 m/s and confirms the stream selection rule,<sup>3,4</sup> which predicts a deviation of the convective velocity for  $M_c > 0.5$ . Convective velocity measurements are likely to be sensitive to the imaging technique employed. The overall trend of a deviation at higher convective Mach number is clearly confirmed. The histogram, however, is a unique addition to the growing body of convective velocity measurements in supersonic shear layers and helps describe the behavior of structures in a more detailed fashion.

In summary, the utility of a newly developed temporally resolved flow visualization system has been demonstrated by its application to a Mach 1.3 axisymmetric jet to extract both qualitative and quantitative information. The additional details that accompany the full set of images provide for a better understanding of the dynamic behavior of structures. This additional information can be used in various ways of studying high-speed flows. For example, the technique has already been used in studies to correlate the production of jet

noise with the behavior of structures within the mixing layer<sup>14</sup> and is currently being combined with planar Doppler velocimetry to yield a quantitative velocity measurement technique for high-speed flows.<sup>15</sup>

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