Three-component velocity and acceleration measurement using FLEET

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The femtosecond laser electronic excitation and tagging (FLEET) method has been used to measure three components of velocity and acceleration for the first time. A jet of pure N_2 issuing into atmospheric pressure air was probed by the FLEET system. The femtosecond laser was focused down to a point to create a small measurement volume in the flow. The long-lived lifetime of this fluorescence was used to measure the location of the tagged particles at different times. Simultaneous images of the flow were taken from two orthogonal views using a mirror assembly and a single intensified CCD camera, allowing two components of velocity to be measured in each view. These different velocity components were combined to determine three orthogonal velocity components. The differences between subsequent velocity components could be used to measure the acceleration. Velocity accuracy and precision were roughly estimated to be ±4 m/s and ±10 m/s respectively. These errors were small compared to the ~100 m/s velocity of the subsonic jet studied.

I. Introduction

While a variety of different velocity measurement technologies have been developed and used to study fluid mechanics in recent years, these measurements have not been adapted widely to large scale facilities because they often require seeding the facilities with particles or (sometimes toxic) gases. "Unseeded" techniques have long been sought for making velocity measurements in both large and small scale wind tunnels. Some techniques that allow measurements in unseeded air or N_2 include Filtered Raleigh Scattering (FRS), Interferometric Rayleigh Scattering (IRS), RELIEF[1], ozone tagging velocimetry (OTV)[2] which requires O_2, and APART[3] which requires both O_2 and N_2 to be present. Each technique has its advantages and disadvantages involving complexity of the setup, optical access requirements and other considerations. A new technique, known as FLEET, recently developed at Princeton University[4,5,6] is a molecular tagging velocimetry (MTV) technique wherein a femtosecond laser dissociates N_2 in a flow and multiple images are acquired from the long lived fluorescence associated with nitrogen atom recombination back to molecular nitrogen. The velocity is determined by dividing the measured displacement of the captured fluorescence by the time separation between the exposures. The FLEET technique has the following advantageous features compared with other techniques: (1) it excites naturally-present N_2 so it can be used in N_2 or air flows so it does not require additional gas or particle seeding; (2) excitation and detection are both at a visible wavelength, so special UV or IR windows are not required; (3) only a single laser and camera are required which simplifies setup and operation; (4) the technique has been shown to work over a large range of pressures and (5) the technique can easily be extended to measure thousands of samples per second. The technique

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is thus applicable to a wide range of wind tunnels and, owing to the long fluorescence lifetime, it can potentially be used to acquire precise single-shot velocity measurements from subsonic through hypersonic regimes.

FLEET has previously been used to probe along a line, providing velocity profiles.[5,6] In prior work, a single camera and single camera view have been used. By generating a cross pattern, two velocity components were previously measured with FLEET.[5] In the current work, the laser was focused to a small spot using a short focal length lens. A mirror assembly allowed the resulting fluorescence imaged from two different (orthogonal) directions on a single camera. Several exposures were obtained on the camera to provide raw particle-path data from which two sets of two velocity components could be measured. These two velocity vectors were then combined to determine all three velocity components. Subsequent velocity measurements could then be used to determine the acceleration of the tagged fluid.

II. Experimental Setup

The amplified ultrafast laser system consisted of a Mai Tai® Spectra-Physics oscillator and a Coherent Hidra amplifier, capable of delivering 100 fs pulses at a wavelength of 800 nm with energies up to 3 mJ, at a repetition rate of 10 Hz. To acquire the velocimetry data in the present experiment, the laser was operated at ~1 mJ/pulse. Lower-than-maximum laser energy was used to avoid laser-induced breakdown which was audibly detected and which decreases the time-delayed FLEET signal.

The laser beam was transmitted to a second room where the rest of the experiment was located. A schematic of the measurement system is shown in Figure 1. To generate a small measurement region, a 5-cm focal-length lens was used to focus the fs laser light. The circular shaped measurement volume was observed to be as small as 0.6 mm diameter (based on observation of the Rayleigh scattering, as shown in the middle panel of Fig. 2). The resulting fluorescence was imaged by a Princeton Instruments PI-MAX:512 (Gen III) gated intensified charge-coupled device (ICCD). The camera had 19 μm x 19 μm pixels (with an effective pixel size of 24 μm x 24 μm) on a 12.4 mm x 12.4 mm chip. The camera gate was operated in burst mode so that the intensifier could be pulsed several times in a single camera frame readout. At burst timings of <8 μs the measured intensity was attenuated, so measurements were obtained with >8 μs timing. The camera gain was set to the maximum of 255. The camera's HQ photocathode had ~45% quantum efficiency in the red spectral region where the long-lived FLEET signal is strongest.[6]

The observed fluorescence is from the 1st-positive emission from molecular nitrogen (with vibrational features in the range of ~550-700 nm). The fluorescence was imaged with an F/1.2 50-mm focal length lens, through a mirror system shown in Figure 1. A pair of orthogonally oriented mirrors placed close to the camera lens (M3 and M4) split the camera's view into two directions as shown. Two more mirrors (M2 and M5) directed these views towards the measurement volume. These two views were aligned to be at a right angle with respect to each other. The N_2 jet flow was provided by a ¼" outer diameter nylon tube supplied with N_2, which is shown in the top-right corner of the figure. N_2 gas was used because it was readily available to provide a flow, FLEET excites N_2, pure N_2 provides a higher signal than air and also because there is interest in developing FLEET for NASA facilities that use N_2 as the test gas, such as the National Transonic Facility (NTF).

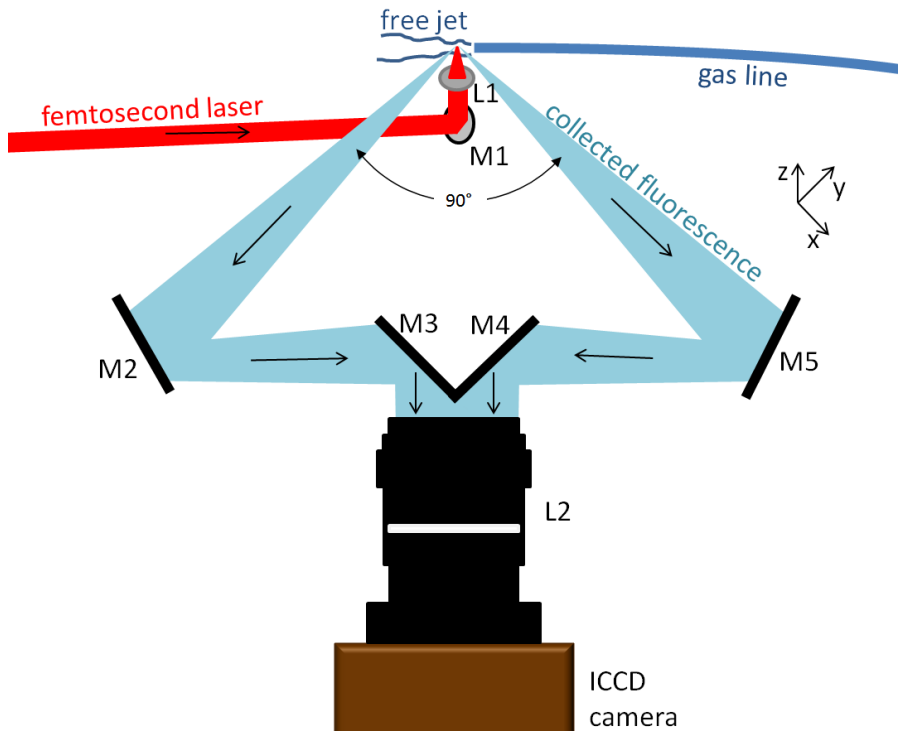

Figure 1. Schematic of detection setup showing camera, mirrors and setup of laser (shown in red) and the path of collected fluorescence (shown in blue with arrows). M1-M5 are mirrors with M2-M5 attached to a single alignment rail. L1 is a 5-cm focal-length spherical lens. L2 is an F/1.2 50-mm focal length camera lens.

III. Results

Figure 2 shows an example of raw images obtained during the experiment. The left column shows images obtained from the left camera view and right column shows the right camera view. The top row of images shows the images acquired of a pattern of square dots (known as a *dotcard*). The dots were 1.588 mm (1/16") squares located on 3.175 mm (1/8") centers. Images were acquired sequentially with the dotcard oriented normal to each of the two camera views. The dotcard was affixed to a rigid panel and was attached to a rotation stage so that it could be oriented normal to the camera views and so the angle between the camera views could be measured. The dotcards were illuminated with room lights and a long exposure was used to obtain these averaged images. These were analyzed to determine the magnification of the images, which was about 5.1 pixels/mm. The second row of images was acquired coincident in time with the laser firing using a 2 μsec gate. Rayleigh scattering from the gas at the location of the laser focus shows as the small circular spot in the image. The tube providing the N_2 jet flow was illuminated by scattered laser light. When the camera was delayed further in time, as in the bottom row of images, the Rayleigh and scattered laser light was blocked by the intensifier and only the FLEET signal was recorded. By double pulsing the intensifier with two 2 μsec gates started 40 μsec apart, two images of the excited N_2 gas were obtained. Two components of velocity were then obtained from each image, left and right. Since the two camera views were orthogonal, the three components of velocity were obtained. Vertical displacement in both left and right images corresponds to the (same) vertical velocity component in the laboratory (resulting in a redundant measurement). However, side-to-side displacement in the two images corresponds to independent measurement of two orthogonal velocity components. Hundreds of such images were obtained to measure the gas velocity exiting the tube.

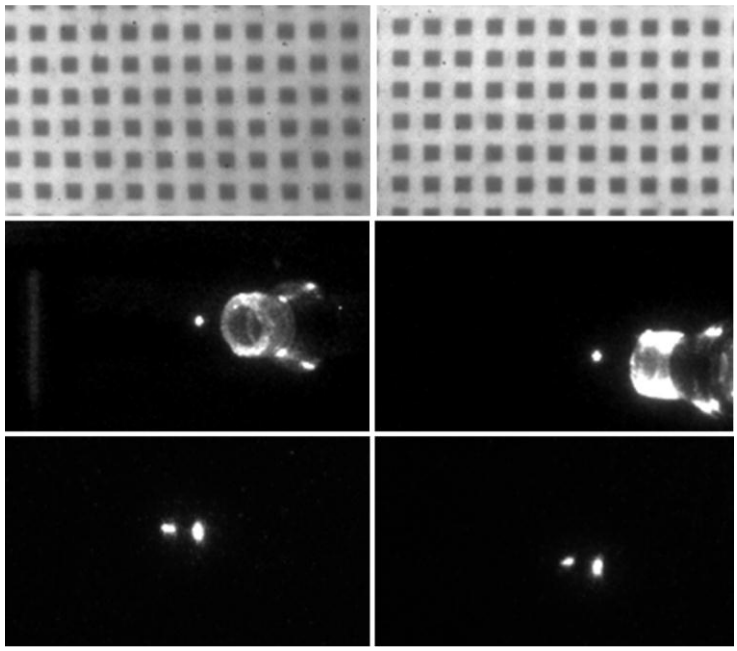

Figure 2. Raw data used for 2-exposure velocity measurement. Left column shows the left camera view and the right column shows the right camera view. Top row shows images obtained of the dotcard oriented normal to the displayed view. Middle row shows an image acquired coincident with the laser pulse, which simultaneously illuminates the flow tube and generates Rayleigh scattering at the focal point of the laser. Bottom row shows FLEET images containing successive exposures of the same tagged gas molecules acquired 40 μsec apart. Flow is from right to left in the images.

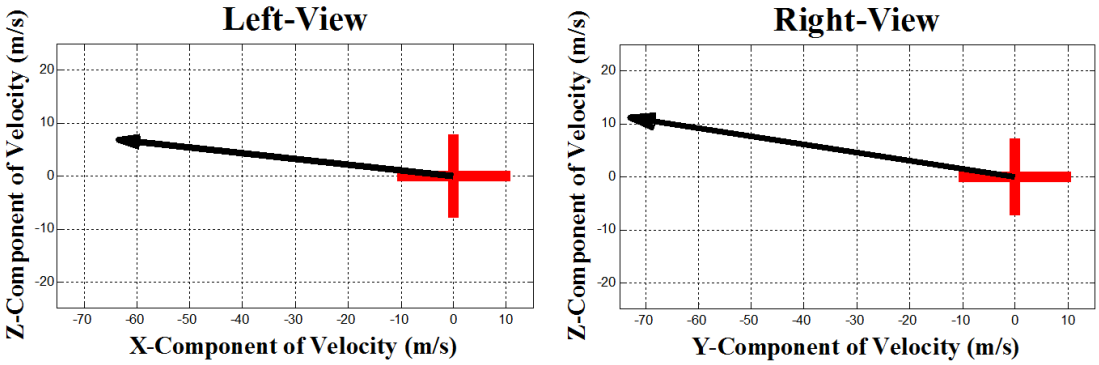

Figure 3. Mean velocity measurements resulting from FLEET images shown in Fig. 2. Red crosses show ±one standard deviation in the measurement.

Displacements of the tagged fluid in the images were computed using MATLAB's weighted-centroid-finding routine *regionprops*. Outlier displacements greater than 3-σ were removed. The displacement, in pixels, was divided by the image magnification of 5.1 pixels/mm to determine the displacement in mm. This was divided by the time separation between the exposures, 40 μsec, to determine the gas velocity. As expected from this subsonic jet flow, velocities of tens of meters per second were obtained. By analyzing approximately 100 single-shot images, means and standard deviations were obtained. Figure 3 shows the resulting mean velocities. The vectors represent the mean velocity vectors as indicated and the red vertical and horizontal bars represent 1-σ of mean velocity components. Note that the jet was somewhat unsteady and consequently the standard deviations contain contributions from unsteadiness of the jet as well as random measurement error. The standard deviation of ~10 m/s then provides an upper limit on the measurement precision. A steadier, more laminar flow could be used in the future to minimize flow velocity fluctuations, providing a better indication of the technique's potential measurement precision. An indication of accuracy can be obtained by comparing the mean z or vertical velocity components. The z velocity obtained from both views should be identical. Instead, they differ by about 4 meters per second, which provides a lower limit of the measurement accuracy (measurement accuracy is, at best 4 m/s, at least for the

current setup, experimental settings and flowfield). A better measure of the accuracy of the technique could be obtained by comparing the measurement to an accepted velocity measurement method such as a particle-based method (laser Doppler velocimetry or particle image velocimetry).

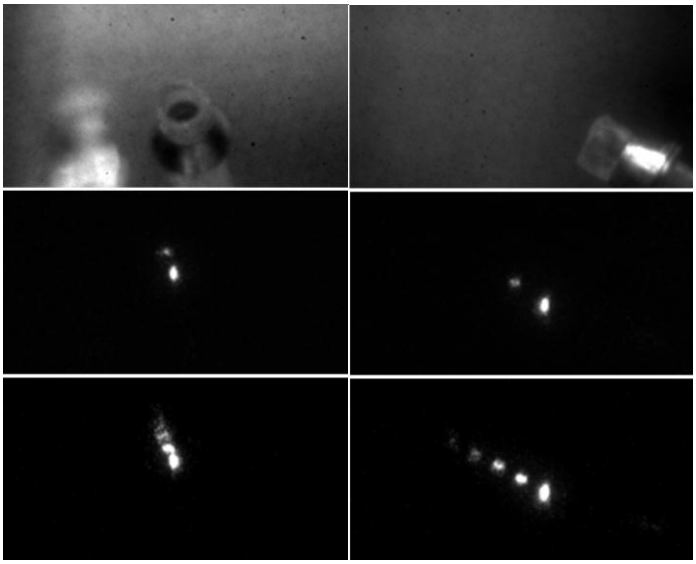

Figure 4. Raw data used for velocity measurements with the jet positioned differently from Fig. 2. As in Fig. 2, the left column shows the left camera view and the right column shows the right camera view. The top row shows the jet exit illuminated by room lights, with a long camera exposure. The middle row shows FLEET images containing two successive 2 μsec exposures of the same tagged gas molecules acquired 40 μsec apart. The bottom row shows five successive 2 μsec exposures of the same tagged gas molecules acquired at 30 μsec intervals. Flow is from bottom right to top left in the images.

Figure 4 shows images acquired with the jet oriented to give a larger z-component velocity. Two-exposure and five-exposure images were obtained. Figure 5 shows additional single-shot measurements using the five-exposure settings. Usable single-shot data was obtained on most shots even with the five-exposure images. The final exposure was obtained more than 150 μsec after the laser pulse, demonstrating the long-lived fluorescence of the FLEET processes. This long-lived fluorescence makes it possible to measure precise velocities even in relatively low speed flows (10's of meters per second). Gas could also be tagged upstream of a test article (a wing for example) and can be monitored as it passes over the article.

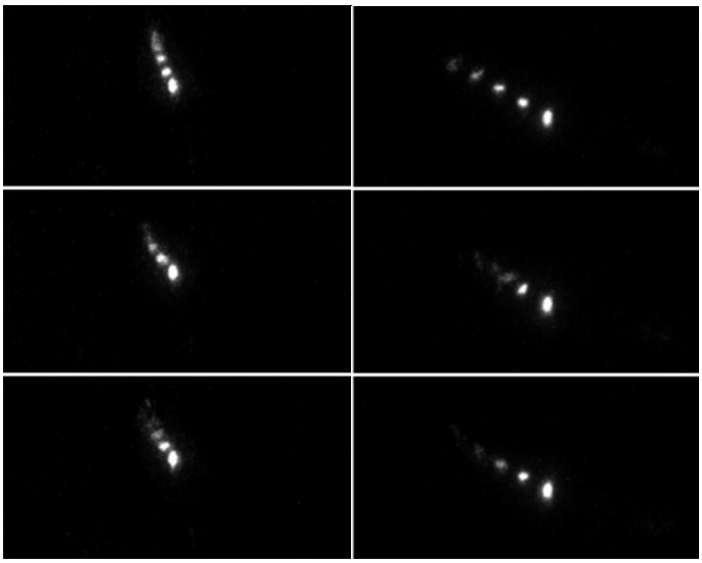

Figure 5. Each row shows a pair of 5 exposure images obtained with a single laser pulse at the same conditions used in Fig. 4. These three realizations were obtained in successive laser shots at 10 Hz.

Obtaining multiple exposures also allows the acceleration of the tagged fluid to be obtained. Images such as those in the bottom row of Fig. 4 were analyzed to determine the trajectory of the tagged fluid, the sequence of resulting velocity vectors and the acceleration of the tagged fluid. Figure 6 shows the resulting particle path (red dots), and velocity and acceleration vectors for one of the camera views. The gas is observed to continue mostly in a straight line, but it is decelerating as it issues into the ambient air.

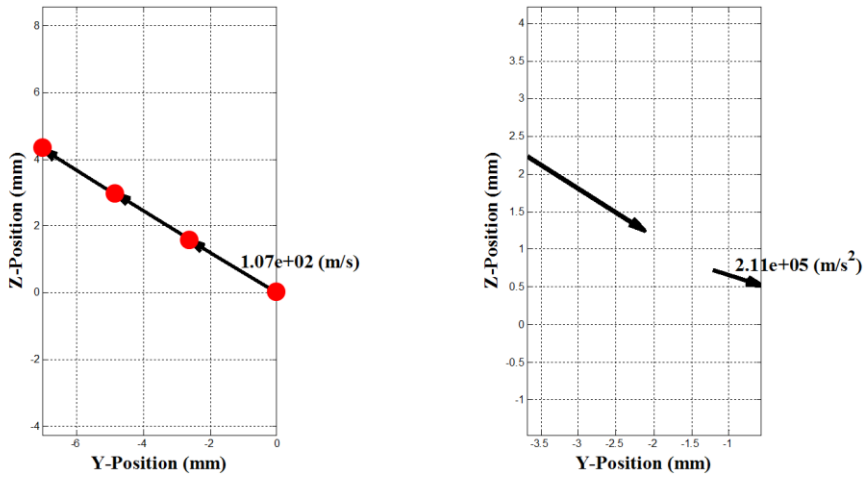

Figure 6. Particle path (red dots), with measured velocity vectors (left) and acceleration vectors (right) of tagged gas obtained for data obtained at the conditions of Fig. 4 (bottom row) and Fig. 5.

While this paper reports a successful demonstration of three component particle path, velocity, and acceleration using the FLEET method, some changes could improve the apparatus or the characterization of the apparatus. An improved method of aligning the two viewing angles should be developed. In the current experiment, the two views were aligned approximately to be orthogonal by eye. Then the dotcard was oriented to minimize perspective distortion in the images with the intention of precisely measuring the viewing angles based on the angle of the dotcard (measured from the rotation stage which had 1 degree gradations). Unfortunately, when the camera was re-focused, the repeatability of the method was determined to be only ±10 degrees. The mean of these two measurements was 91 degrees, negligibly close to 90 degrees (considering the measurement uncertainty), so the two views were assumed to be orthogonal for the purposes of this paper and no correction was applied to the resulting velocity vectors. In future measurements, it is recommended that an optical jig be developed to allow the two views to be mechanically aligned to be orthogonal. Furthermore, careful observation of the individual images show that the second and subsequent exposures were significantly non-circular, indicating that the flow was somewhat turbulent. A steadier, more laminar flow should be used to better assess the precision of the instrument. Finally, the accuracy of the instrument could be assessed by comparing with an accepted velocimeter.

The experiment could have been performed using two or more synchronized cameras. However, the use of a single camera reduced setup cost and complexity though it reduces the signal intensity by approximately a factor of two. Nonetheless, only one camera was available for the current experiments.

IV. Conclusions

This paper reports three-component particle path, velocity and acceleration measurement using FLEET for the first time. Measurements were obtained in a subsonic N_2 jet. The method could be further characterized by performing measurements in a laminar flow facility and by comparing with an accepted velocity measurement method. Such non-intrusive, unseeded particle path, velocity and acceleration measurements could provide quantitative data for comparison with computational fluid dynamics simulations of flows in wind tunnel facilities.

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