Burst-mode femtosecond laser electronic excitation tagging (FLEET) for kHz–MHz seedless velocimetry

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Burst-mode femtosecond laser electronic excitation tagging (FLEET) of nitrogen is introduced for tracking the velocity field in high-speed flows at kHz–MHz repetition rates without the use of added tracers. A custom-built Nd:glass femtosecond laser is used to produce 500 pulses per burst with pulses having a temporal separation as short as 1 μs, an energy of 120 μJ, and a duration of 274 fs. This enables two orders of magnitude higher measurement bandwidth over conventional kHz-rate FLEET velocimetry. Characteristics of the optical system are described, along with a demonstration of time-resolved velocity measurements with ~0.5% precision in a supersonic slot jet. © 2019 Optical Society of America

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Accurate velocity measurements in supersonic and hypersonic test facilities are important for the design and validation of performance models for high-speed flight vehicles. Probe-based measurements traditionally used in subsonic facilities have limited spatial and temporal resolution and can also significantly perturb the flow around high-speed test articles. Optical techniques such as particle image velocimetry (PIV) have been demonstrated at high repetition rates in supersonic flows [1]; however, the accuracy is limited by particle lag in regions with high velocity gradients (*e.g.*, within the boundary layer or across shock fronts). Additional challenges such as limited optical access, particle seeding density, and hardware contamination discourages the use of PIV in many supersonic and hypersonic test facilities. Molecular-tagging-based velocimetry techniques address several challenges of optical measurements in wind tunnel environments. Introducing a gas-phase tracer such as nitric-oxide into the flow allows for velocity measurements that are free of particle lag [2, 3]. However, flow mixing and diffusion can limit the ability of tracers to reach the desired measurement region, and tracer injection can perturb the flow being analyzed. Recent progress on Krypton tagging has shown promise for reliable supersonic velocity measurements [4, 5] as it is chemically inert and less prone to alter the flow physics.

Unseeded molecular tagging techniques take advantage of the fluorescence properties of molecules already present in flow and are a promising approach for non-intrusive velocimetry in ground test facilities. Raman excitation and laser-induced electronic fluorescence (RELIEF) [6], Rayleigh scattering [7], and air photolysis and recombination tracking (APART) [8] have been demonstrated but are subject to their own limitations, such as complex setup requiring multiple lasers to be spatially overlapped.

Femtosecond (fs) laser electronic excitation tagging (FLEET) [9-12] is a technique that has been developed and demonstrated for velocimetry measurements based on the dissociation and tracking of fluorescence that occurs during the subsequent recombination of nitrogen molecules. FLEET can be performed in a line-of-sight configuration with a single focused laser beam and camera, requiring only one small window for optical access [12–14]. While this approach has been shown to be applicable over a wide range of flow conditions and test facilities, data acquisition has generally been limited to a repetition rate of 1 kHz. This is not sufficient to track the evolution of dynamical features in high-speed flows, such as turbulence and shock-flow interactions [15, 16]. This limitation was overcome recently by using a custom-built burst-mode laser that could operate at 100 kHz with 100 ps pulse durations in a 10 ms long burst [17]. Time-resolved flow measurements have been made using this technique, referred to as PLEET [18], but due to the longer pulse duration and lower peak power, the minimum energy threshold is ~2 orders of magnitude higher than FLEET and is not feasible at MHz rates with available laser energies.

This work aims to increase the repetition rate of FLEET measurements by up to 3 orders of magnitude by employing a burst-mode fs laser capable of generating signals at rates up to 1 MHz. This laser is modified from a previous design that is described in detail in Ref. [19]. The current design enables a more compact laser architecture with fewer amplification stages. Figures 1a and

1b show the time-bandwidth beam characteristics of the laser source, with a Gaussian transform limited pulse width of 274 fs at a central wavelength of 1063.6 nm. This differs from prior FLEET measurements using Ti:Sapphire lasers near 800 or 400 nm [9-16], which show an improvement in signal intensity at shorter wavelengths [10]. It is of interest, therefore, to evaluate FLEET measurements using the current laser because of differences in laser wavelength, beam quality, and pulse width. The quality of the compressed transform-limited beam was measured using a D4σ technique. The 4-mm-diameter beam was shown to diverge slightly astigmatically, resulting in an average M^2 of 3.15, as shown in Fig. 1c. Burst profiles for 200 kHz and 1 MHz repetition rates can be seen in Fig. 1d, with 200 ± 19.2 μJ/pulse and 120 ± 11.3 μJ/pulse, respectively. The burst duration of the laser is about 0.8 ms. However, the pulse energy of the laser during the beginning of the burst is too low to achieve sufficient signal. Therefore, FLEET measurements are only acquired for a duration of 0.5 ms. A +30 mm focal length achromatic lens doublet was used to produce a tightly focused spot, resulting in a calculated peak irradiance of 77.2 ± 7.4 TW/cm^2 and 46.3 ± 4.4 TW/cm^2, respectively, at the probe volume. The optical path of the laser was enclosed in lens tubes to mitigate environmental variations in the refractive index along the beam path. Optics were also placed on translating mounts to provide higher precision for focusing the laser spot to the desired measurement region of interest.

FLEET velocimetry was performed in a pressure-fed converging-diverging slot jet (Fig. 2) with a design Mach number of 3.6 and perfect expansion to atmosphere at 89 bar. Due to pressure losses in the system, supply pressures could be varied from 0 to 82.7 bar to attain a range from subsonic to supersonic velocities. FLEET has been shown to be quenched in the presence of oxygen [9]. This is due to a tendency of dissociated N atoms to recombine into NO rather than N_2 molecules, which bypasses the FLEET emission mechanism. Hence, a gas mixing system allowed testing with either air or pure nitrogen to evaluate applicability for different wind tunnel conditions.

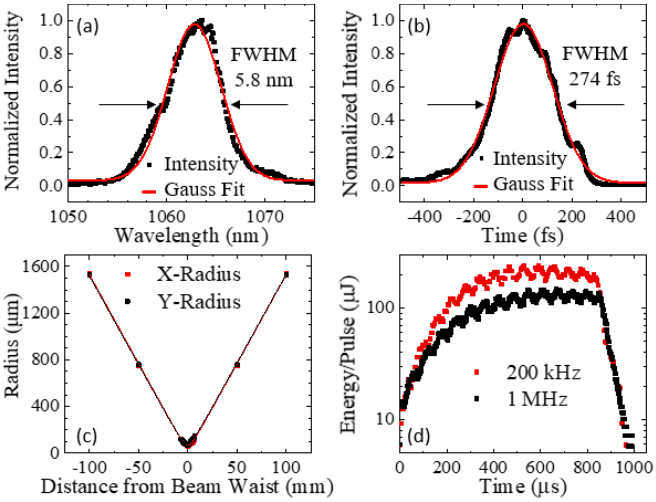

Fig. 1. Parameters of fs laser, including (a) frequency domain bandwidth, (b) temporal domain pulse width, (c) beam quality divergence profiles after temporal compression with $M^2 = 2.97$ and 3.33 in x and y directions, respectively, and (d) burst profiles for 200 kHz and 1 MHz repetition rates.

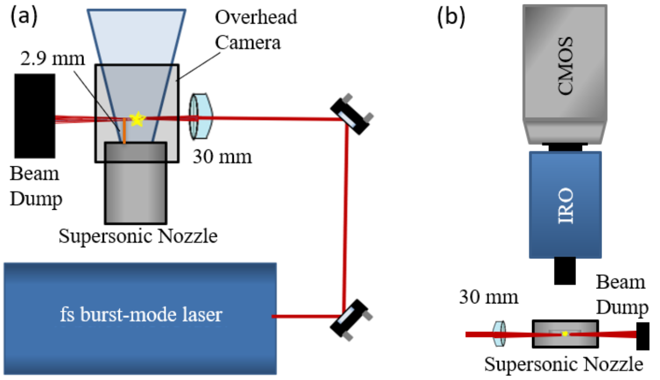

Fig. 2. (a) Top view of FLEET experiment showing laser delivery to probe location through 30 mm focusing lens and (b) front view showing top-down placement of high-speed intensified camera.

The FLEET probe laser was aligned precisely across the exit of the supersonic nozzle to 2.8 mm from from the exit plane. A high-speed CMOS camera (Photron, SA-Z Fastcam) was used to capture images of the FLEET signal as it propagated downstream. An image intensifier (LaVision, HS-IRO) with an S20 photocathode and P46 phosphor was used with the high-speed camera to provide precise time gating and increase in signal level. Sequences of tagged nitrogen spots were generated at both 200 kHz and 1 MHz rates. Images were captured at 200 kHz for all datasets. A pixel resolution of 384×160 was achieved with a Nikon 50 mm lens set to an f-stop of $f/1.2$ and coupled with a 14 mm extension ring. The intensified camera was positioned above the nozzle to look downward onto the flow. The magnification of the imaging system was 32 μm/pixel. With a zoom lens and/or longer extension rings, the resolution can be improved. However, there is a trade-off between resolution and frame size since the signal can move significant distances in the high-speed flows being studied.

Originally, a 600 +/-25 nm bandpass filter was used to isolate the FLEET signal, but the reduction in signal posed a challenge at lower excitation energy. Instead, the gate of the camera was delayed to 70 ns after the laser pulses to avoid laser scattering and ensure that only the FLEET fluorescence was captured. This approach provided a significant improvement in signal level.

Datasets were collected at upstream supply pressures of 30–70 bar to evaluate the measurement technique performance over a range of flow velocities (see Fig. 3). For all of these operating conditions, the exit flow of the nozzle was slightly overexpanded. For the 68.9 bar condition, an intensifier gate of 800 ns was used with a gain of 65%, and for the 34.5 bar case the gate was 900 ns with a gain of 73%. A noticeable decrease in signal intensity was observed in the lower supply pressures. As there was no nitrogen co-flow, this was likely due to FLEET signal quenching from the entrainment of quiescent air. As such, the gain on the intensifier needed to be increased, leading to a lower signal to noise ratio. To evaluate the applicability of high-speed FLEET measurements to a wider range of facilities, the experiment was replicated with air as the supply fluid at 68.9 bar. Due to much higher signal quenching, the intensifer gate was set to 1500 ns with a gain of 85% to enable imaging of the less intense FLEET signals.

The tagged nitrogen molecules formed a spot at the beam focus, and at a framing rate of 200 kHz, the velocity could be obtained by measuring the displacement of this spot every 5 μs. First the images were cropped to local regions around each spot with user input. A noise threshold for the image was found from the background values and any pixel below this threshold was set to zero. In FLEET velocimetry, a Gaussian intensity distribution can be fit across the spot to find the centroid location. Two dimensional Gaussian surface fitting was applied to the data collected in this experiment; however, this algorithm produced a large proportion of outlier velocity measurements due to poor fitting.

Three methods of centroid finding were then applied to the FLEET images, including a simple centroid, a bounding box centroid, and a weighted centroid. For each measurement, the largest discrepancy between centroid finding algorithms was taken to be the uncertainty in the velocity measurement. Figure 3a shows a trend of decreasing spot quality with decreasing supply pressure. Representative signals are shown for each supply pressure with associated results from the area centroid, bounding box centroid, and weighted centroid shown in cyan, red, and black, respectively. This leads to a correlated increase in the measurement uncertainty at lower pressures. Additionally, the uncertainty with the experiment in air was significantly higher due to poorer relative spot quality causing more relative error in centroid finding. As shown in Fig. 3b, the uncertainties vary from 14.3 m/s at 34.5 bar (2.6%) to 7.3 m/s at 68.9 bar (1.14%), with the uncertainty for the air measurement being 53.2 m/s (8.3%).

Due to strong dependence on the binarization threshold and spot shapes associated with the area and bounding box centroid methods, an image correlation based velocity measurement method was implemented instead to reduce uncertainty. The correlation method does not require thresholding, making it more robust at low signal levels. Between successive images of the same spot, a cross-correlation map of all possible displacements was created. The peak of this map was treated as the most likely displacement for the spot. A two pixel wide median filter was applied to each image before correlation to eliminate small amounts of spatial non-uniformity. Bicubic interpolation near the correlation peak was applied to achieve sub-pixel accuracy on displacement measurements. Figure 4 shows representative correlation maps for velocity measurements over the range of conditions tested.

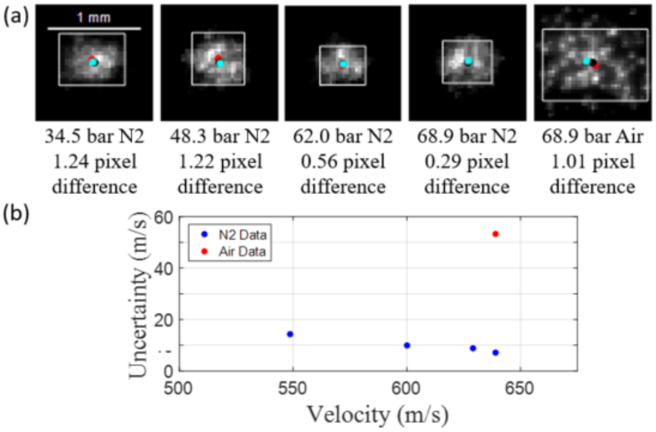

Fig. 3. (a) Representative spot finding with area centroid (cyan dot), intensity weighted centroid (black dot), and bounding box (white box) with centroid (red dot); and (b) associated trend of uncertainty in velocity measurements for different pressures with pure N_2 and air.

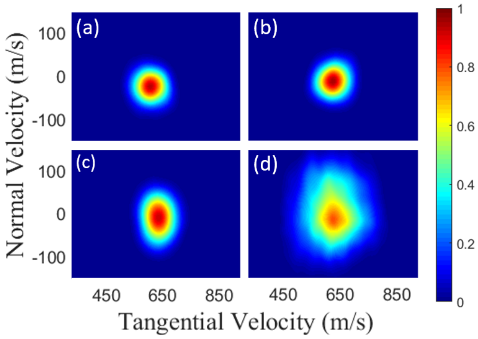

Fig. 4. Correlation maps for displacement in (a) 34.5 bar nitrogen, (b) 48.3 bar Nitrogen, (c) 68.9 bar Nitrogen, and (d) 68.9 bar air.

For the nitrogen cases, the correlation map is generally a Gaussian distribution about a clear peak, and the pixel shift is well defined. For the air case, the correlation map quality is lower, but a clear peak is still present. In general, there was good agreement between the weighted centroid and correlation-based approaches. The velocity is reported as the mean value of both methods, and the uncertainty is considered to be the absolute difference between both results at a given data point. Figure 5a shows the time history of measured velocity in nitrogen at 68.9 and 48.3 bar at the nozzle exit. The mean values for these measurements are 639 and 600 m/s with standard deviations of 9.1 and 8.7 m/s, respectively. The uncertainties for these pressures using this method are 2.75 m/s (0.43%) and 3.32 m/s (0.55%), which is a marked improvement over using a centroid-only approach. Since the deviation of the measured flow velocity is larger than the uncertainty, it is concluded that this measurement method is sensitive enough to capture the unsteady flow fluctuations. Figure 5b shows the average trend of velocity with uncertainty bands.

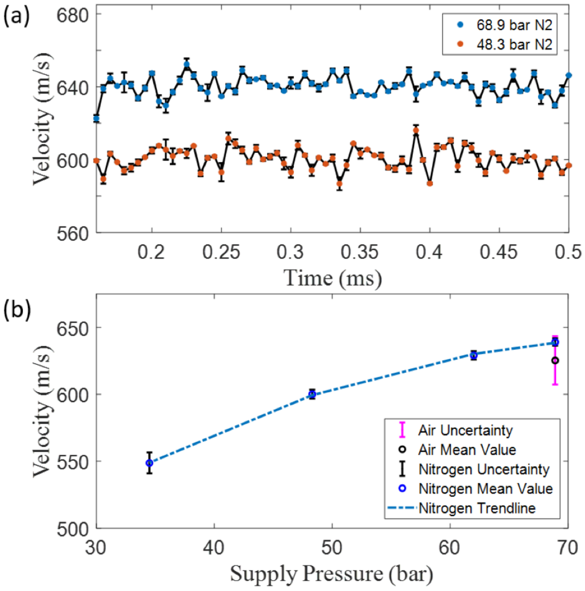

Fig. 5. (a) Velocity time history for 68.9 and 48.3 bar supply pressures with nitrogen. (b) Average velocities and uncertainties for all tested conditions with nitrogen and air.

The uncertainty grows with decreasing pressure due to poorer spot quality. The expected velocity for a perfect expansion case for this nozzle at 89 bar is 651 m/s. While this condition could not be achieved, the results trend toward this value as pressure increases, showing good agreement between theory and measurements. The uncertainty of the air measurement is much larger as compared to the nitrogen measurements. To improve the accuracy of this technique for use in air, a more sensitive imaging system or higher laser energy is required.

Due to limitations in the framing rate of the imaging system, time-resolved data could not be taken above 200 kHz, but the laser was operated at 1 MHz to test the image quality that could be obtained for the pulse energies available at the highest possible repetition rate of the custom burst-mode fs laser. The gate and gain of the intensifier were set to 400 ns and 72%, respectively. Figure 6 shows results of two successive frames taken 5 μs apart with 1 MHz laser excitation. Each of the two frames captures all of the spots generated by the 1 MHz laser that have convected downstream and which display sufficient fluorescence to be detected on the intensified camera. An example of five individual FLEET spots and their shift during the 5 μs time delay between images is marked in Fig. 6a. Centroid finding is then performed as previously described to calculate all velocities, as shown in Fig. 6b.

Unlike prior work with 1 kHz or even 100 kHz excitation, 1 MHz excitation allows for simultaneous measurement of velocity at multiple streamwise locations in supersonic flows without the use of beam-splitting optics. In addition, the measurement rate at each location is limited only by the framing rate of the imaging system. The rate of 200 kHz is higher than that demonstrated in prior work and is accomplished with two orders of magnitude lower excitation energiy than prior 100 kHz PLEET measurements [13]. Moreover, with the current signal levels, available commercial MHz-rate image intensifiers and cameras will make it feasible to collect multi-point data at rates up to 1 MHz. Note that the signal-to-noise ratio for the images captured in this experiment is ~120, but the laser energy at the 1 MHz rate fluctuates above and below the lower signal threshold for FLEET, so only some acquisitions provide useful data at this repetition rate. As such further improvement in the laser energy amplitude and consistency would increase the data rate in these experiments.

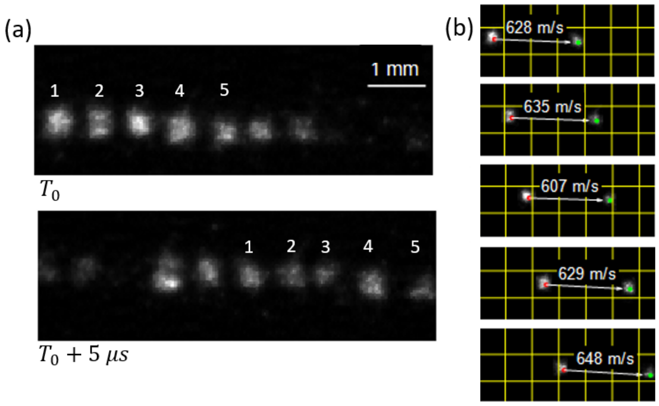

Fig. 6. (a) Raw data collected with 1 MHz laser excitation. (b) Five velocities measured simultaneously along a streamline with 1 MHz laser excitation (grid spacing is 1 mm).

In conclusion, a compact burst-mode laser platform capable of producing high-energy femtosecond pulses has been demonstrated for excitation of FLEET signals at rates up to 1 MHz. A supersonic nozzle was used as a test case for proof-of-concept velocity measurements in supersonic flows with uncertainties of ~0.5%. Time-resolved velocimetry was conducted in unseeded nitrogen and air flows using the FLEET technique with laser excitation rates of 200 kHz to 1 MHz. The image collection rate of 200 kHz represents a significant improvement over prior FLEET measurements. However, single-shot measurements were achieved with 1 MHz laser excitation and demonstrate the feasibility for MHz-rate seedless velocimetry using intensified camera systems that are currently commercially available. With 1 MHz excitation and 200 kHz detection in the current work, five or more downstream locations could be tracked simultaneously for high-speed multipoint velocimetry. This work demonstrates an approach to increasing the spatio-temporal resolution of FLEET measurements, with the potential for further improvements in laser excitation energy, image collection efficiency, and framing rate of the intesnsified camera system in future work.

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