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High-repetition-rate interferometric Rayleigh scattering for flow-velocity measurements

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Abstract

High-repetition-rate interferometric-Rayleigh-scattering (IRS) velocimetry is demonstrated for non-intrusive, high-speed flow-velocity measurements. High temporal resolution is obtained with a quasi-continuous burst-mode laser that is capable of operating at 10–100 kHz, providing 10-ms bursts with pulse widths of 5–1000 ns and pulse energy > 100 mJ at 532 nm. Coupled with a high-speed camera system, the IRS method is based on imaging the flow field through an etalon with 8-GHz free spectral range and capturing the Doppler shift of the Rayleigh-scattered light from the flow at multiple points having constructive interference. The seed-laser linewidth permits a laser linewidth of < 150 MHz at 532 nm. The technique is demonstrated in a high-speed jet, and high-repetition-rate image sequences are shown.

Optical diagnostic techniques based on high repetition rates are currently capable of providing temporally and spatially resolved measurements of flow and combustion properties [1–4]. These measurements are proving to be unique and crucial in tracking fast-occurring phenomena such as those encountered in high-speed turbulent flows.

The key features of the instrument system used in these high-repetition-rate investigations are the high-power laser burst and the narrow linewidth. These features allow the capture of spatially and temporally varying flow parameters, including velocity, density, pressure, and temperature. Turbulent flows such as those occurring in the inner structure of supersonic-jet cores can be tracked.

The burst-mode laser is seeded with a continuous-wave (CW) laser for narrow-linewidth generation [1]. This permits the performance of instantaneous, high-repetition-rate, interferometric Rayleigh scattering (IRS) and filtered Rayleigh scattering (FRS) [5–8] measurements that require a spectrally narrow laser beam. In this effort, the "giant" or "stretched" pulse capability was incorporated to provide variable pulse duration (and variable bandwidth) from 5 ns to 1 µs with relatively high power (> 100 mJ/pulse) that allows prevention of dielectric breakdown and optical damage. In addition, longer pulses may have narrower bandwidths defined by Heisenberg's uncertainty principle.

Among the numerous optical-based velocimetry techniques that have been developed over the past several decades for non-reacting and reacting flows, most utilize lasers for either illumination or resonant/non-resonant molecular-excitation-based tracking. A comprehensive list of such techniques may include seeded methods, such as planar, stereoscopic, and tomographic Particle-Imaging Velocimetry (PIV) [9], laser Doppler velocimetry (LDV) [10], planar Doppler velocimetry (PDV) [11], molecular-tagging velocimetry (MTV) [12], and laser-induced fluorescence (LIF) [13], and unseeded techniques, such as Raman excitation plus laser-induced electronic fluorescence (RELIEF) [14], air photolysis and recombination tracking (APART) [15], femtosecond-laser electronic-excitation tagging (FLEET) [16], and Rayleigh scattering techniques including FRS and IRS [5–8, 17–20]. Most of these techniques have shortcomings related to signal levels, requirement of flow

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containing certain particles or molecules, lack of sensitivity at high flow velocities, and complexity in harsh environments.

As compared to all of the velocimetry techniques outlined above, the Rayleigh-scattering-based IRS technique has the following advantages for various high-speed wind tunnels: (1) absence of active seeding, (2) ability to measure several flow parameters simultaneously, and (3) applicability over a wide range of flow temperatures and gases (e.g., air, N_2, vitiated air, and argon). Although IRS lacks the two-dimensional (2D) measurement capability and may have low signal levels, it is inherently a multi-point, multi-parameter measurement technique [7].

The basic principle of the IRS technique is that Rayleigh-scattered light from the flow of interest is imaged through a Fabry–Perot interferometer (FPI, 'etalon') [5–8]. The FPI is used here in 'static' imaging mode (i.e., without changing the mirror separation), and its theoretical transfer function is an Airy function that produces a 2D interference fringe pattern comprising concentric rings at various radiuses. The shape and spacing of this circular constructive interference pattern depends on the angle of the object plane locations, the etalon mirror separation and the reflectivity of the mirrors, and the linewidth of the light source [6]. When light from a narrow-linewidth laser is imaged through an etalon, the image intensity pattern is a delta function convolved with the theoretical Airy transmission function of the FPI [6]. When Rayleigh scattering is imaged through an etalon, a series of broadened spots separated by the Airy ring spacing is formed which contain spectral information from the volume probed, including the Rayleigh scattering lineshape which contains spectral broadening and shift information. This theory and the particular properties, parameters, resolution, and quality characteristics of the etalon [5, 6] are used to derive the frequency shift and thus velocity from the image intensity at various locations. Density and temperature information can also potentially be obtained with this method. The physical coordinate relation between the object plane and the image plane is given by the image-forming optics magnification.

Since the transmission properties of the etalon depend both on the wavelength and on the angle of incidence of light, the image contains spatial-frequency information that allows the Doppler shift due to flow velocity to be determined at multiple locations in the flow. The velocity can be obtained based on the Doppler-frequency shift Δf_d through the following expression [5, 6]:

$$\Delta f_\mathrm{d} = \frac{\vec{s} - \vec{o}}{\lambda} \cdot \vec{V}. \quad (1)$$

Here, $\vec{o}$ is the unit vector in the direction of the incident/object laser light, $\vec{s}$ is the unit vector in the scattering/observation direction, λ is the wavelength of the light, and $\vec{V}$ is the flow-velocity vector.

The IRS technique has been performed in the past at low repetition rates (e.g., 10 Hz) for instantaneous measurements of flow parameters [7, 8, 18, 19] and at high sampling rates (e.g., 32 kHz) using continuous-wave (CW) lasers for time-integrated (30-μs) flow measurements [6] and using CW laser sources combined with EM-CCD cameras for imaging a line in the flow at 5 kHz [20]. In this investigation, the high-repetition-rate and high-power burst is successfully demonstrated for providing instantaneous (e.g., with time exposures < 100 ns) IRS measurements at a rate of 10 kHz or higher for resolving the time scales associated with high-speed turbulent-flow phenomena. In the present study, a step toward time-resolved measurements was demonstrated with 10-kHz IRS for multi-point flow-velocity determination.

The present investigation was focused on the demonstration of burst-mode IRS for measuring a single component of velocity. The IRS technique depends on an elastic process that does not change with the flow. However, Rayleigh scattering is weak and diffuse, and the transmission efficiency of the etalon is low. Therefore, high-energy laser sources and a high-efficiency light-collection system over large solid angles are required for improving the signal-to-noise ratio (SNR) of the measurements. The maximum pulse energy is limited by laser-induced gas breakdown near the focus of the laser beam. The burst-mode laser offers two major advantages: (1) high pulse energy with adjustable pulse length (up to 1000 ns at 532 nm) that permits substantially more energy to be delivered at the measurement volume and (2) high repetition rate (up to 100 kHz) over the duration of the burst that allows temporal resolution of high-speed flow events. High pulse energy, in turn, may alleviate the need for signal collection over a large solid angle (i.e., "fast" optics), which is often difficult to implement in wind-tunnel facilities. Since the Rayleigh scattering signal is approximately at the same wavelength as the incident laser (except for a small Doppler shift and line broadening), interference from particles and surfaces can occur. The SNR can be improved by introducing a molecular filter (such as iodine for 532 nm) for removing unwanted scattered light [5, 8]. The IRS technique can also minimize such localized interferences during image analysis.

The pulse energy is also limited by the onset of ionization and plasma generation, which causes bright flashes that overpower the Rayleigh signal. Plasma breakdown occurs when the peak power exceeds a certain threshold, which imposes an upper limit on the total energy that can be used for a given spot size and pulse width. Rayleigh scattering is a linear process, where the signal level increases with the laser energy and is not dependent on the laser pulse width. It can, therefore, be advantageous to deliver energy over a longer period of time ("Giant-Pulse" mode) to avoid ionization or damage to wind-tunnel windows. For these reasons the burst-mode laser with the tunable-pulse-width feature offers a significant advantage.

Another critical parameter for IRS measurements is the laser linewidth, which dictates the uncertainties associated with the measured velocity. Since IRS velocimetry is a Doppler-shift technique, the peak of the Doppler-shifted signal can be easily separated from narrow reference interference rings produced by a narrow-linewidth laser. If a high-resolution etalon is used, the laser linewidth will determine the lower limit of the Doppler shift that can be measured accurately. The peaks of the Rayleigh signal and the reference rings are normally fitted with a theoretical model to solve for the Doppler shift and other parameters, which will be treated in detail in the discussion on data fitting.

A schematic of the setup used in this investigation is shown in Fig. 1 with an acquired IRS sample image in a quiescent flow. In this setup, the narrow-linewidth light at 532 nm from the burst-mode laser is focused to form the laser-beam waist in the measurement region of interest via focusing lenses. Rayleigh-scattered light from the beam-waist region is collected and collimated by lenses in a direction normal to the vertical polarization plane to maximize the signal. This collimated light then passes through a solid etalon with an 8.3-GHz free spectral range (FSR), and the measurement region is imaged via a focusing lens onto a high-speed, intensified complementary-metal-oxide-semiconductor (CMOS) camera. The reference beam ('Ref') from the laser source (not Rayleigh scattered) is introduced into the IRS optical path through the polarizer. The polarizer is used to combine the Rayleigh signal with the reference laser light. The laser wavelength is monitored by a wavemeter through an optical fiber (O.F.). The burst-mode laser is operated at a rate of 10 kHz. The laser is configured to allow operation in a special "Giant-Pulse" mode, which allows stretching of the pulse width from 5 ns to 1 μs with > 100 mJ/pulse.

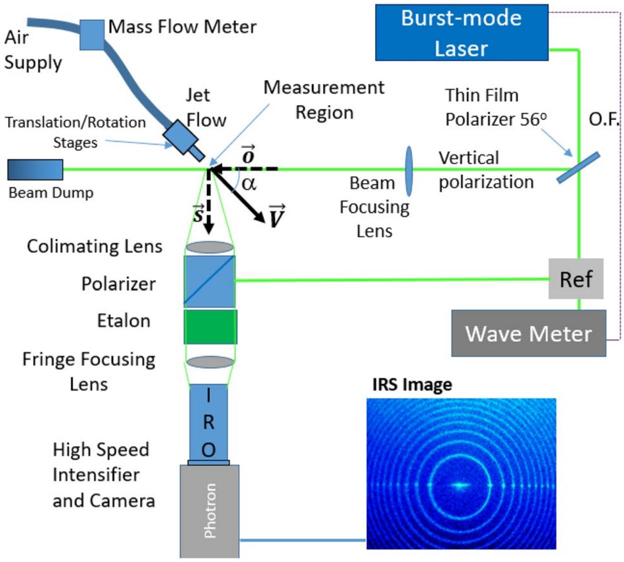

Fig. 1 Schematic of IRS system for focused-laser-beam interrogation

In this study, the pulse energy was ~ 100 mJ/pulse, and each burst contained about 100 pulses of 50-nsec duration. A high-speed Photron SA-Z CMOS camera and a LaVision IRO intensifier were used to record the IRS images. The intensifier gain was set at ~ 60% of the maximum value. The field of view was $\sim 4 \times 4\ \mathrm{mm}^2$. IRS velocity measurements were made in a 4-mm-inner-diameter lab-scale jet, and the measurements were performed approximately four diameters downstream of the nozzle exit. The image consists of a set of concentric bright rings that result from constructive interference of the reference-source and a set of aligned bright spots from the focused imaging region. The etalon allows transmission of light from discrete radial points from the image center; the transmitted light forms a constructive interference pattern where each ring corresponds to a different view angle [5, 6]. Thus, a radial cut through the image provides the spectra of the scattered and reference light sources at a few spatial locations. The horizontal line discrete pattern is thus the image of the laser beam at the probed volume and spectrally filtered by the etalon.

Radial displacement of the scattered light relative to each reference ring is due to the Doppler shift associated with the velocity at that reference point, while radial broadening of the width of the spots relative to the reference rings is due to molecular broadening [5]. The Doppler shift, which varies at each point along the line pattern, will yield flow velocity measurements at various positions. The radial broadening is dependent on the molecular weight and temperature, which can be used for extracting temperature if the gas composition and pressure are known (assuming the laser heating effect is negligible). Also, since the integrated Rayleigh-scattered signal intensity is proportional to the number density of the gas molecules (for a given gas composition), the system can be calibrated to measure the density of the gas [5, 6, 17].

The detected Doppler shifts of scattered light from the incident object beam $\vec{O}$ in the direction of the collected scattered laser light $\vec{S}$ are due to the component of velocity lying in the bi-sector of the plane formed by the two vectors $\vec{O}$ and $\vec{S}$ [5, 6]. Then, with the jet nozzle set at an angle $\alpha = 45°$ with respect to the laser beam and the scattering direction (Fig. 1), the main flow velocity is obtained by

$$V = \Delta f \cdot \lambda / \sqrt{2}. \tag{2}$$

When a narrow seed-laser source having a linewidth of < 50 MHz was used, the linewidth of the amplified pulse at 532 nm was < 150 MHz at a 10-kHz rate measured by a wavemeter. It should be noted that the linewidth measurement based on etalon rings is dependent on the quality of

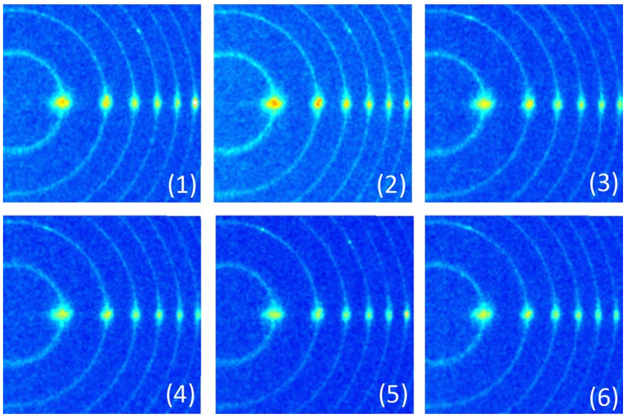

Fig. 2 Typical 10-kHz image sequence of IRS with zero flow speed

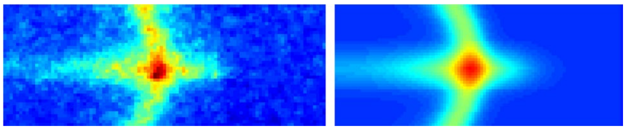

Fig. 3 Typical local fitting of IRS image with zero flow speed

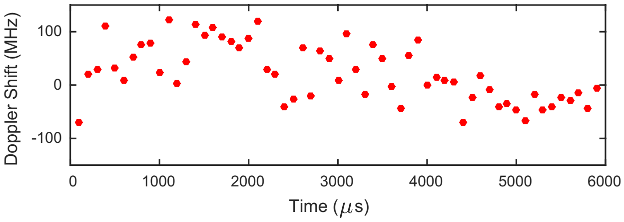

Fig. 4 Doppler and fitting uncertainties for IRS with zero flow speed

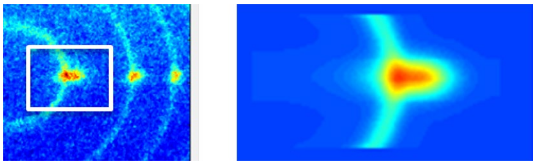

Fig. 5 IRS image fitting with a free jet. Flow speed is ~300 m/s

the etalon—a quality such as the surface flatness. Therefore, the ring thickness shown in the IRS images could be broader than the actual laser linewidth. The etalon quality is also dependent on the degree to which the two solid etalon surfaces are parallel. High-quality surface flatness better than $\lambda/100$ is required for a high-finesse etalon. For a typical Mach-1 flow of ~340 m/s, the calculated Doppler shift is ~900 MHz, based on Eq. (2). Separation of the 900-MHz-shifted Rayleigh-scattering signal peak from the 150-MHz reference rings should be a simple task.

A typical IRS image sequence obtained in room air at a 10-kHz rate is shown in Fig. 2. As explained previously, the reference light imaged through the etalon generates the circular rings, and the Rayleigh-scattering signal from the focused laser beam generates the discrete points in the image-sequence centerlines. Here, the points along the centerline represent Rayleigh-scattering signals from different discrete positions, which yield velocities of the flow simultaneously at multiple points. Since the flow speed is zero, no Doppler shift was observed. The Rayleigh-scattering points overlap well with the reference rings. The size of the laser rings do not change during the burst duration, indicating the stability of the laser wavelength. When the laser rings were fitted with the results from theoretical calculations, frequency fluctuations of 20 MHz (standard deviation) were observed.

Figure 3 shows an example of a detailed raw image with a 100×60 pixel^2 sub-region and the corresponding theoretical model that was calculated using the data-fitting program. The theoretical model assumes that the light scattered from the laser beam is distributed spatially as a Gaussian of constant height perpendicular to the direction of the beam and has a constant intensity along the direction of the beam. Scattered light, focused laser light (broadened by the Rayleigh-scattering process), and the uniform background (having the same spectrum as the laser source) were found to be approximately Gaussian. The fitted laser linewidth was determined to be ~500 MHz, which is significantly broader than the linewidth measured with the high-resolution wavemeter. The quality of the etalon used for the Rayleigh scattering is responsible for this broadened linewidth, as measured from the interference rings. The fitted Rayleigh-scattered linewidth is ~2.2 GHz, which is in agreement with the Tenti linewidth at room-air conditions of 2.2 GHz [5].

With the use of Eq. (1), Doppler-shifted frequencies within a burst showed that the mean is 22 MHz and that the standard deviation is ±54 MHz (Fig. 4), which represents the bias and precision error in the Doppler shift; these shifts correspond to 8.4 and ±20 m/s, respectively. Note that the 8.3-GHz FSR of the etalon represents the full scale of the instrument; therefore, as a fraction of instrument range, the bias and precision errors are 0.27 and 0.65% (percent of full scale), respectively. For a 300-m/s flow, 20 m/s corresponds to a 6.7% measurement uncertainty. The accuracy could be improved further with the use of a higher quality etalon.

Figure 5 displays an IRS image detail for a jet flow of ~300 m/s. The corresponding theoretical image that was used for fitting the experimental data is shown on the right. It is obvious that the Rayleigh-scattering signal is Doppler-shifted relative to the reference rings because of the flow velocity. The laser line probes a profile across the centerline of the jet and shows the Doppler shift being largest near its center and diminishing towards the edges of the jet

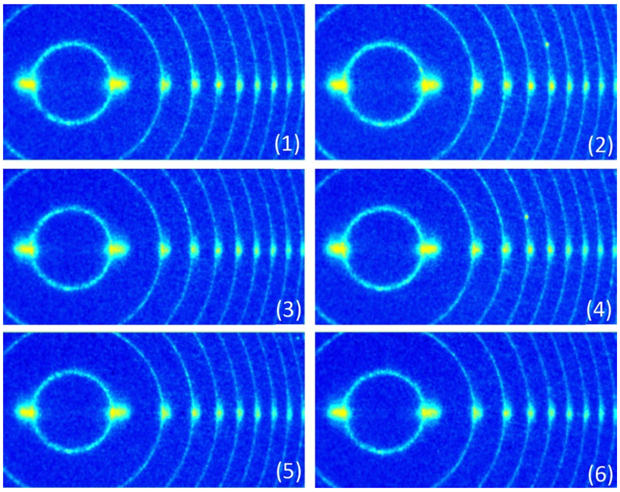

Fig. 6 10-kHz IRS image sequence with flow speed of ~ 300 m/s

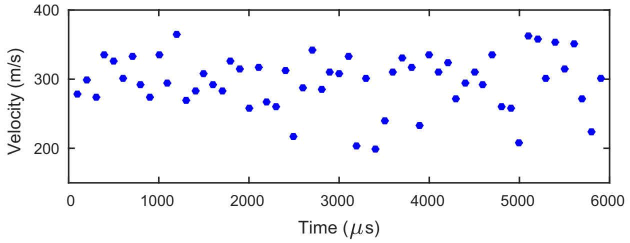

Fig. 7 Flow-velocity profile measured by 10-kHz IRS

where the velocity is near zero. The images were acquired at 10 kHz, and Fig. 6 shows a six-image sequence as an example of high-speed IRS. The Doppler-shifted frequencies have significant fluctuations due to the fluctuations associated with the flow. The fitted Doppler shift for the particular image shown in Fig. 5 is 706 MHz, which corresponds to a flow speed of 266 m/s. The linewidth of the Rayleigh-scattered signal is ~ 1.86 GHz because of the slightly lower flow temperature.

Figure 7 shows the time-resolved velocity of the jet flow acquired at a rate of 10 kHz. Sixty measured data points are shown. The flow velocities fluctuate from 200 to 370 m/s. The velocity-measurement uncertainty is ~ 20 m/s, based on the analysis of the no-flow conditions. For this flow-speed range, the 10-kHz repetition rate does not appear to be sufficiently fast to capture the flow dynamics. Thus, the plan is to apply a 100-kHz-rate IRS velocity measurement in the future. In addition, since multiple points in the jet centerline are available from each ring location, a time-resolved, centerline jet-velocity profile is also feasible. With multiple laser-beam lines at different locations, a time-resolved evolution of the spatial profile as well as a second component of the velocity can also be obtained [7]. Also, varying (or scanning) the laser frequency or the etalon mirror distance would allow measurement of the velocity in various flow points.

In conclusion, high-repetition-rate, burst-mode-laser-based IRS velocimetry was demonstrated at 10 kHz in a high-speed turbulent jet with a mean velocity of ~ 300 m/s. The pulse-train within the 10-ms-duration burst enabled the measurement of time-resolved velocity in a high-speed jet flow. The laser capabilities included operation in a special “Giant-Pulse” mode, which allows the pulse width to be stretched from 5 ns up to 1 μs and a linewidth of < 150 MHz at 532 nm, as measured with a wavemeter. The IRS measurement uncertainties were analyzed, and a data-fitting program was developed for IRS image processing. The investigation demonstrated high-repetition IRS for time-resolved turbulence velocity measurements. It provided new insights on the measurement capabilities of burst-mode lasers for time-resolved, multipoint, instantaneous, and non-intrusive supersonic flow diagnostics.

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