LASER VELOCIMETER FOR STUDIES OF MICROGRAVITY COMBUSTION FLOWFIELDS

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INTRODUCTION

We are currently developing a velocimeter based on modulated filtered Rayleigh scattering (MFRS), utilizing diode lasers to make measurements in an unseeded gas or flame. MFRS is a novel variation of filtered Rayleigh scattering, utilizing modulation absorption spectroscopy to detect a strong absorption of a weak Rayleigh scattered signal. A rubidium (Rb) vapor filter is used to provide the relatively strong absorption and semiconductor diode lasers generate the relatively weak Rayleigh scattered signal. Alkali metal vapors have a high optical depth at modest vapor pressures, and their narrow linewidth is ideally suited for high-resolution velocimetry; the compact, rugged construction of diode lasers makes them ideally suited for microgravity experimentation. Molecular Rayleigh scattering of laser light simplifies flow measurements as it obviates the complications of flow-seeding. The MFRS velocimeter should offer an attractive alternative to comparable systems, providing a relatively inexpensive means of measuring velocity in unseeded flows and flames.

Filtered Rayleigh scattering is an established technique for measuring flow velocity and thermodynamic properties in a gas or flame. We improve the detectability of the weak Rayleigh scattered signal by using modulation techniques, utilizing the tunability of diode lasers to implement heterodyne detection.[1] The injection current, and hence the frequency, of the diode laser is dithered at the rate of several kHz. The high frequency modulation results in a modulated absorption through the rubidium filter in a reference and a scattering arm, and a corresponding modulation appears in the detector outputs that are fed into two separate lock-in amplifiers. If these lock-in amplifiers are synchronized with the function generator that drives the frequency modulation, then very high levels of background rejection are possible since the lock-ins are both frequency and phase selective.[2]

Two basic modes of operation have been devised for the MFRS velocimeter: the sweep mode of operation and the frequency-locked mode of operation.[3] In sweep mode of operation the laser is tuned relatively slowly across the entire profile of the rubidium D_2 transition (approximately 11 GHz centered at 780 nm), while simultaneously dithering the frequency. In preliminary experiments the lock-in amplifier was set to extract the 2^{nd}-harmonic of the modulation frequency (*2f* detection). The Doppler frequency shift due to velocity in the probe volume is measured by cross-correlating the shifted *2f* scattering profile to the *2f* reference profile. The S/N is poor for Rayleigh scattering measurements, and so the lock-in output time constant has to be relatively long to collect reliable data. The sweep period must be correspondingly increased, which is the primary disadvantage of the sweep mode of operation. In preliminary investigations of the sweep mode of operation, with 25 mW of laser power in the probe volume an output time constant of at least 100 ms was required to measure the Rayleigh scattered signal reliably. Ideally the ramp period should be much longer than the output time constant, and modulation period much less. With this time constant, ramp frequencies greater than 0.1 Hz distorted the profile, and so the temporal resolution of the MFRS velocimeter was limited to 10 s.

An alternative to sweeping the laser across the Rb D_2-profile is to tune the diode to the edge of one of the Doppler broadened components in the multiplet and lock the laser to a desired frequency while modulating about this frequency. A shift in the Rayleigh scattered frequency due to changes in Doppler shift would result in a change in absorption and thus in the magnitude of the *2f* signal. There is additional experimental complexity in the frequency-locked mode of operation, because of the need to stabilize the laser and to account for density fluctuations in the probe volume. A drift in laser frequency would be misinterpreted as a Doppler frequency shift of the Rayleigh scattered signal and attributed to a change in flow velocity. In addition, in the frequency-locked mode of operation the velocity can only be correlated to the amplitude of the filtered Doppler-shifted Rayleigh scattered signal provided that scattering intensity fluctuations due to density fluctuations are normalized out.

An extended-cavity diode laser (ECDL) is currently being built to obviate difficulties associated with preliminary attempts to stabilize a free-running diode. Specifically, we are building an ECDL that uses a grazing-incidence diffraction grating as the wavelength selective element.[4,5] Laser power in the probe volume is a concern since the power output from ECDLs is practically limited to < 50 mW. We therefore intend to inject the cavity output into an AR-coated broad stripe diode (P=1.5 W). The resulting extended cavity diode laser master oscillator power amplifier (ECDL-MOPA) system should provide frequency stable, single-mode, relatively high power lasing for the MFRS velocimeter in frequency-locked mode of operation.

We are also currently developing a ratioed detection scheme for the Rayleigh scattered signal that will provide a frequency reference that is independent of the signal intensity. The Rayleigh scattered signal from the photomultiplier tube (PMT) in the scattering arm is output to two separate lock-in amplifiers. The outputs from the lock-in amplifiers, each set to extract a different harmonic of the modulated signal from the PMT, are ratioed, resulting in a frequency dependent, scattering-intensity independent signal. In essence, we extract different Fourier components of the modulated signal and ratio them.

EXPERIMENTAL SETUP

The experimental setup for the sweep mode of operation is shown in Figure 1. The single-mode GaAlAs diode (Hitachi HL7851), mounted in a diode laser head (ILX Lightwave LDM-4420), is excited with an ultra-low noise current controller (ILX Lightwave LDX-3620) that is specified to be stable to ≤10 ppm over 10-30 minutes. The temperature of the diode was controlled with a spectroscopic grade thermoelectric temperature controller (ILX Lightwave LDT-5910B) with a long-term stability of less than ±0.01°C. Dry nitrogen is bled into the laser head to prevent condensation during operation. The diode emits at 780 nm when operating at approximately 125 mA and -3°C with a linear tuning rate of approximately -2.1 GHz/mA. Therefore, a triangular current ramp of amplitude 5 mA scans repetitively across the entire hyperfine structure of the D_2 line that extends over approximately 10.5 GHz at Doppler limited resolution. A good compromise between lock-in signal strength and profile resolution was established with a modulation current amplitude of 0.20 mA. The modulation sine wave and triangular sweep are produced by separate function generators (Exact 200MSP and Stanford Research Systems DS345) and combined in a summing amplifier (Stanford Research Systems SR560) before input to the current driver.

The laser beam is collimated and a small portion (< 1%) of the beam is split off to a reference arm, and passes through a 10 cm long room temperature cell containing Rb vapor in natural isotopic abundance (72.2% ^{85}Rb and 27.8% ^{87}Rb) before being recorded by an avalanche photodiode (Hamamatsu C5460). The majority of the laser beam passes to the probe volume. A series of six anti-reflection coated lenses are used to collect the scattered light from the probe volume and relay it through a Rb cell identical to that in the reference arm, a ±1 nm narrow-band filter (Barr Associates) and focus it onto a side-looking PMT (Hamamatsu R636-10). The PMT is biased at ~1000 V to give good radiant sensitivity while maintaining a linear response. The narrow band filter greatly reduces interference from ambient light while passing the Rayleigh scattered signal with high efficiency (80% peak transmittance). For these preliminary experiments we chose standard off-the-shelf lenses for the scattering arm optics. The lenses were chosen with the help of OSLO LT freeware, with a design objective of filling the PMT photocathode with high transmission efficiency. The collection F/# of ~1.2 was achieved using a pair of 100mm diameter, 120.8 mm focal length plano-convex lenses (Melles Griot LPX215/076).

Two lock-in amplifiers (Stanford Research Systems SR830) are synchronized with the modulation signal and run in *2f* mode so that their output approximates the 2^{nd}-derivative of the Rb D_2-profile. The lock-in output signals are digitized with a 1.25 Msample/s, 12-bit National Instruments data acquisition board (PCI-MIO-16E-1). A virtual instrument (VI) was developed with National Instruments LabView G-programming language to trigger acquisition and save the acquired profiles to a binary file.

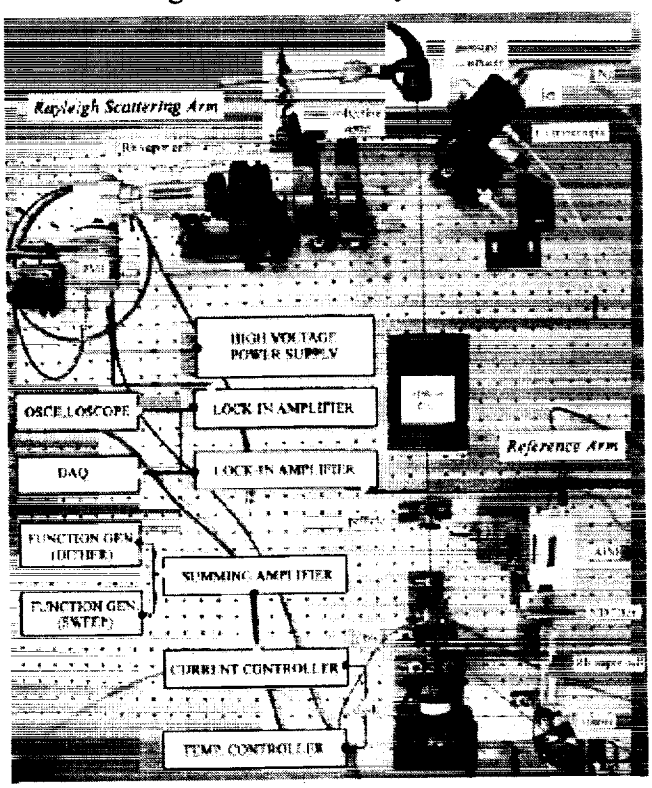

Figure 1. MFRS experimental setup.

In the frequency-locked mode of operation, the reference arm is used to lock the ECDL-MOPA system to the edge of some feature in the absorption profile. A proportional-integral-differential (PID) controller was built, and will eventually stabilize the ECDL-MOPA system at the zero crossing of this edge. The error signal due to drift in laser frequency is fed back to a piezoelectric transducer that tunes the wavelength selective element in the cavity. One additional lock-in amplifier in the scattering arm completes the required modifications for operation of the MFRS velocimeter in frequency-locked mode.

RESULTS

We have demonstrated measurement of gas velocity in an unseeded nitrogen jet.[3] Velocity measurements were made nominally 9 nozzle diameters (28 mm) downstream of a converging nozzle. The geometry of the velocimeter was set to measure the axial velocity of the jet. A post-processing VI was written to cross correlate the signal and reference profiles, and to convert the Doppler frequency shift to a velocity measurement. Figure 2 shows a sample screen from this VI after post-processing a series of velocity measurements obtained during a single run. The sweep frequency for this run was 0.1 Hz and the laser was swept through approximately 4GHz to cover

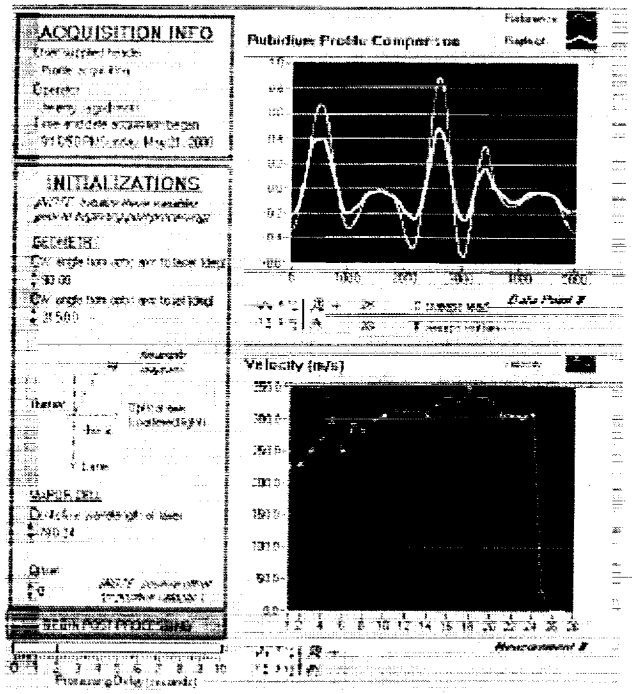

Figure 2. LabView post-processing routine

the two strong absorption features of ^{85}Rb that are separated by about 3 GHz. The reduced sweep range enables the profile to be scanned with lower distortion for a given sweep rate. The laser frequency was modulated at the rate of 2 kHz with a modulation amplitude of approximately 300 MHz and the lock-in output time constant was set to 100 ms.

The plenum pressure and temperature were recorded manually for each laser sweep (duration 10 s). A relatively rapid acceleration is provided by a 12.5 mm (1/2-in) radius of curvature up to the throat of the converging nozzle, and isentropic expansion was assumed in the core flow to calculate the maximum theoretical velocity for comparison to the measured velocity. In these preliminary experiments with molecular Rayleigh scattering the imaged length of the probe volume is estimated to be ~5 mm so the measurements average over flow gradients and cannot be directly compared to a calculated jet velocity field.

CONCLUSIONS

We have demonstrated preliminary velocity measurements in an unseeded nitrogen jet by MFRS. The current spatial and temporal resolution are limited to ~5 mm and 10 s respectively, and work is in progress to improve the system performance.

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