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Laser diode self-mixing technique for liquid velocimetry

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ABSTRACT

Using the self-mixing technique, or optical feedback interferometry, fluid velocity measurements of water seeded with titanium dioxide have been performed using a laser diode to measure the effect of the seeding particle concentration and also the pump speed of the flow. The velocimeter utilises commercially available laser diodes with a built-in photodiode for detection of the self-mixing effect. The device has demonstrated an accuracy better than 10% for liquid flow velocities up to 1.5 m/s with a concentration of scattering particles in the range of 0.8–0.03%. This is an improvement of one order of magnitude compared to previous experiments. The proposed velocimeter is to be developed further for application in gas-jet measurements.

1. Introduction

Self-mixing (SM) Laser Doppler Velocimetry is an interferometric technique based on the detection of backscattered light coupled back into the laser cavity [1]. Light scattered off a moving target is Doppler shifted with a frequency f_d proportional to the velocity V of a moving target given by

$$f_d = 2\frac{\vec{V}\cdot\vec{n}}{\lambda} = 2\frac{V\cos\alpha}{\lambda} \qquad (1)$$

where $\vec{n}$ is the unit vector in the direction in which the light propagates, λ is the wavelength of the lasing light, and α is the angle between the laser axis and the velocity vector of the target. The backscattered light for the SM technique appears from the process of scattering or reflecting of light off a target. When a small amount of light is coupled back into the cavity, the field inside is weakly perturbed by the back-scattered light leading to beating with a frequency proportional to the difference between the wavelength of the emitted and returning light.

The geometry of the self-mixing system is such that backscattered light is collected within an angle, which depends on the optics of the system. The amount of collected light can be calculated using optical constants and the density of the particles which the light predominantly scatters off.

The SM technique requires minimal optics and can be used for many applications such as vibration, distance and displacement measurements, and also for the velocity characterisation of solid targets and liquid flows. The motivation of this work is to look into the possibility to use the technique for the characterisation of gaseous flows such as gas-jets which are used for various applications at particle accelerators such as for beam instrumentation [2,3]; for the production and spectroscopy of radioactive isotopes [4]; and as a source of a laser induced plasma in laser-plasma acceleration experiments [5].

For beam instrumentation, a new type of thin sheet shaped gas jet has been developed [2]. The velocity profile of the gas-jet curtain is expected to be in the range of 100–2000 m/s and with a diameter of 1–20 mm. The molecules which are used for gas jets such as nitrogen, argon, or helium have an expected density of 10^9–10^{12} molecules/cm^3 within the chamber [3]. The characterisation of the gas jet velocity profile is required for its optimisation and the self-mixing technique may be ideal to perform this task, however, measurements of gas-jets using this technique have never been performed before.

Mechanical, acoustic and optical techniques are typically used for characterisation of supersonic flows. When applying mechanical techniques [6], a solid object is inserted into the flow, which causes undesirable and rather strong perturbations. Acoustic techniques provide only limited information of the flow and have a low resolution. Optical techniques, which are represented by a broad spectrum of different methods, are the most promising techniques. The most commonly used are Particle Imaging Velocimetry [7], which requires a powerful laser system, and Laser Doppler Velocimetry, which exists in multiple forms [8]. The SM sensor is a compact and low cost laser velocimeter which is the subject of this paper.

2. The self-mixing technique for flow characterisation

The scattering process for liquid and gas targets is different compared to solid targets. For a solid target the entire illuminated

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surface is moving whereas for liquids and gases, scattering occurs off each individual particle. Depending on the amount of particles in the scattering volume, the amount of scattered light coupled back into the laser cavity depends on

(1) the differential cross-section of the laser light on the particles in the liquid,
(2) the solid angle within the scattered light that can be collected by the optical system, and
(3) the volume of flow which is interacting with the laser beam.

A preliminary calculation based on Rayleigh scattering theory [9] of the expected backscattered light shows that it is necessary to have additional seeding particles added to the gas in order to have a sufficient level of signal for self-mixing to occur. The minimum level of feedback is -90 dB for an SM sensor [10]. If a gas-jet, which consists of particles with diameter d and density N, is illuminated with laser light of power P_0, the optical power P_{det} of scattered light within a solid angle $\Delta\Omega$ can be written as

$$P_{\mathrm{det}} = P_0 \eta N z_{\mathrm{d}} \cdot \Delta\Omega \cdot \frac{9\pi^2}{\lambda^4} \cdot d^6 \tag{2}$$

where η is the optical collection efficiency and z_{d} is the depth of the measured volume. Assuming that the size of the particles within the flow are 0.1 nm and a gas jet density of 10^{12} molecules/cm^3, the power attenuation calculated from Eq. (2) is around -240 dB. To achieve a desirable level of feedback for an SM sensor, additional seeding particles with a diameter of at least 10 nm are necessary for an SM velocity measurement.

Generally, the amount of light scattered off small particles strongly depends on the refractive index of the seeders and the surrounding area, the size, shape and orientation of the particles and the observation angle. The refractive index of air is considerably less than that of water, so the amount of light scattered off particles in air is at least one order of magnitude more than with particles of the same size in water. As a result, the size of the seeders for velocimetry of gases can be smaller, and vice versa for water flow measurements larger particles have to be used for a sufficient amount of light to be scattered.

Previous studies of the SM technique have mostly been focused on medical applications with the majority of works concentrating on blood flow measurements. The most commonly used liquid is water which is then seeded to mimic blood. Milk and polystyrene (latex) spheres are often used for seeding the water, sometimes blood itself is added as a seeder. A wide range of literature already exists which covers medical applications of the SM technique. The work by the following groups is a sample of previous studies in this area: [11–16], furthermore molecular dynamic studies were performed by [17].

Velocity measurements of liquid flows have previously been limited to 20 cm/s [14]. We have demonstrated that the self-mixing method has the potential to measure high velocities and measurements have been achieved with velocities of up to 50 m/s for solid targets and up to 1 m/s for liquids [18].

3. Theoretical spectrum of a self-mixing laser signal

Analysis of the SM signal for velocity measurements indicates that the frequency of the self-mixing is proportional to the velocity of the target [11–17]. The spectrum of the SM signal provides information about the signal in the frequency domain and hence the velocity of the target.

In the case of solid targets, the theoretical spectrum of light scattered off a rotating ground glass has been analysed by [19], and it has been shown that the spectrum of the signal is Gaussian. For a laser beam perpendicular to the rotating surface, the spectrum of the scattered light is

$$I(f) \propto \frac{1}{V/w} \exp\left(\frac{-(f-f_{\mathrm{d}})^2}{2(V/w)^2}\right) \tag{3}$$

The amplitude of the scattered spectrum is inversely proportional to the velocity of the target and proportional to the beam waist radius w. The spectrum has a peak at a frequency proportional to the Doppler shift and is broadened proportionally to the velocity of the target and inversely proportional to the beam waist radius.

Assuming that the Brownian motion of the moving particles can be neglected compared to the velocity of the liquid and that the seeders follow the carrier liquid closely, the scattered light is a superposition of the Gaussian spectrum of each independent particle the light scatters off. However, the scattered light is not distributed randomly over $(0, \pi)$ as for a rough surface such as a ground glass, but according to the differential scattering cross-section of the scattering particles. Moreover, the spectrum should be proportional to the integral over the spectrum of all scatters depending on the amount of light they were illuminated with and over the scattering cross-section depending on the solid angle of the collecting optics. Hence, the spectrum of the SM signal is broadened in proportion to the maximum velocity of the fluid and to the distribution of the velocities of the fluid within the illuminated area, which are weighted proportionally to the intensity of the illuminating light. The scattering cross-section function and collecting optics influence the amount of light coupled back into the cavity and therefore the amplitude of the SM signal. The distribution of the velocities of the particles which the light scatters off leads to further broadening of the spectrum.

For liquid in a tube or flow discharging into the atmosphere, the maximum velocity is located at the centre of the flow decreasing towards the edge of the flow according to Poiseuille's law, see Fig. 1. Each group of particles moving with the same velocity produces a spectrum with a dominant frequency. The resulting spectrum consists of a weighted sum of all frequency contributions within the illuminated volume.

In the case of laser light focused onto a target in a way that the width of the laser spot is about the same size across the measuring volume (see Fig. 1a), the intensity of light from illuminated particles moving with identical velocities is the same, so all of them will produce about an equal amount of scattered light. However, the peak amplitude of the spectrum of scattered light reduces with the velocity of the target according to Eq. (3). Fig. 1b schematically shows the spectrum obtained for the case when moving particles contribute equally to the spectrum. The maximum velocity of the fluids is at the cut-off slope of the resulting spectrum.

If the laser light is focused in such a way that it illuminates more intensely on one particular area, see Fig. 1c, then the rest of the moving particles contribute significantly less to the overall spectrum. As a result, the spectrum will have a peak at a frequency corresponding to the velocity of the particles in the area where the light was focused. The peak of the overall spectrum is broadened more compared to the rough surface due to the contribution of particles that move with different velocities and close to the illuminated volume, see Fig. 1d.

Assuming that the laser beam is focused at the centre of the flow, the maximum intensity will be from the particles moving with maximum velocities. If the light is focused elsewhere, the spectrum will still have a peak at a frequency corresponding to the velocity of the illuminated area; however the peak will be broadened even more due to higher frequency components which expand the main peak to the right. The broadening of the spectrum from the particles

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