LASER DIODE VELOCIMETER-MONITOR BASED ON SELF-MIXING TECHNIQUE*

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Abstract

Gas targets are important for a number of accelerator-based applications; in particular as cold targets for collision experiments and beam diagnostics purposes where gas jets have been successfully used as least intrusive beam profile monitors, however, detailed information about the gas jet is important for its optimization and the quality of the beam profile that can be measured with it. A laser velocimeter shall be used for an in-detail characterization of atomic and molecular gas jets and allows investigations into the jet dynamics. Existing methods are currently not efficient enough, hard to build, and rather expensive. A laser velocimeter based on the self-mixing technique can provide unambiguous measurements from a single interferometric channel, realizable in a compact experimental setup that can be installed even in radiation-exposed environments. In this contribution, an introduction to the underlying theory of self-mixing is given, before the design and functioning principle of the velocimeter is described in detail. Finally, preliminary experimental results with different solid targets are presented and an outlook on measurements with fluid and gaseous targets is given.

INTRODUCTION

Given the critical importance of supersonic flows in aerodynamics and turbo machinery, many measuring techniques have been proposed to fully characterize them, ranging from mechanical, to acoustic, to optical ones. Moreover, such flows are also exploited for advanced instrumentation to monitor the properties of charged particle beams. For example, a curtain-shaped beam profile monitor has been developed recently as a least destructive monitor for various types of particle beams [1]. This monitor is based on a neutral gas jet which is shaped into a thin curtain. The ionization of this jet by a crossed charged particle beam can then be used for imaging the 2-dimensional beam profile in the case of high and ultra-high pressure vacuum machines [2]. For such a beam profile monitor, it would be highly desirable to have a compact sensor able to record its velocity and density profile in order to understand the jet dynamics in detail. It should be possible to integrate such monitor in a simple way in an existed set-up to provide accurate information about the velocity and density of the gas jet. The sensor would ideally consist of comparably cheap components.

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There are also other beam profile monitors [3] that are based on a similar principle, and that have demonstrated their capability of monitoring charged particle beams. In order to be able to take a decision about a specific technique to monitor such jets, it is important to understand the underlying measurement principle in detail, its limitations such as maximum velocities and densities that can be covered, as well as circumstances where it can be used. Furthermore, one also needs to find a compromise between the required monitor parameters and the cost of the set-up.

For supersonic flows, mechanical techniques, such as Constant Temperature Anemometry (CTA) and Hot-wire Anemometry (HWA) [4], call for a solid object to be inserted in the flow and result in major perturbation of the investigated system. Acoustic techniques provide only limited information on the flow, jeopardized by both the low resolution and the small number of observable phenomena. This leaves optical techniques as the only real alternative. Within the field of optical techniques, there is a broad spectrum of different methods. The most important one are several types of particle seeding velocimetry methods [5], spectrally resolved Rayleigh scattering [6], laser Doppler velocimetry, and various interferometry techniques [7]. It is worth to consider all of them; however most of them require powerful laser systems or very precise and rather expensive components for set-ups. An alternative is a compact and low cost laser velocimeter which is the subject of this paper.

LASER SELF-MIXING VELOCIMETRY

The gas jet of a beam profile monitor as described in the previous section consists of neutral molecules, such as argon (Ar), molecular nitrogen (N_2), or Helium (He). All molecules move roughly in the same direction with a velocity between 1,000-2,000 m/s. The range of velocities depends on the use of the gas jet, in particular the inlet gas pressure and pressure differential in the system. The velocimeter should measure in this entire range and down to 10 times lower velocities in order to obtain its full velocity profile.

The jet itself will have a diameter of 1-20 mm. Its density depends on the pressure in the chamber, which can vary from 10^{-6} mbar to 10^{-11} mbar. The expected range of the gas-jet density is 10^9–10^{12} particles/cm^3. The velocity will not be constant in all points of the jet, but will be roughly constant in its core. One of the tasks of the monitor is to measure this velocity distribution.

The idea of measuring density and velocity simultaneously comes from the fact that the density can be found in the amplitude of the SM signal. The latter depends on the quantity of radiation backscattered from the target and will increase with increasing density. The velocity can be measured in parallel by observing the change in frequency.

Self-Mixing Theory

Laser self-mixing is used to characterize some properties of a moving object by using both, laser light and the cavity where the laser originates from. It is based on the following principle: laser light is scattered/reflected from a moving target, and returned into the laser cavity. The laser plays the rule of a coherent heterodyne receiver and at the same time the amplifier of the signal. The initial radiation interacts with the scattered or reflected radiation and produces a signal in both, the power and frequency spectrum of the laser. It is a system without a complex optical system, based on an in-expensive and compact diode laser, which can be easily installed and used to provide central information about the target, such as velocity, distances of movement and property of the surface (for solid target), density and property of scattered molecules (for liquids and/or gases).

The self-mixing system can be described as if the scattered target was an additional mirror, and the whole system was a laser with an external cavity with length *L*, which depends on the velocity of the target as it shown in Fig.1. From a theoretical perspective, SM can be described either by solving a set of equations for the electric field and carrier density of laser diode (LD) with additional terms responsible for the effect of the feedback from the target [8] or by assigning a reflection coefficient to the target and calculating the reflectivity of the laser mirrors and then using it as a reflectivity index in steady solution for initial LD description. The result of both descriptions is the same and the resulting power can be described as

$$\mathrm{P} = \mathrm{P}_0 \ (1 + mF(wt)) \,, \qquad (1)$$

where $t = 2\ L/c$ is the external time of flight, w is the frequency after feedback, P_0 and P are the optical power without and with feedback, respectively, and m is a modulation parameter. Depending on the feedback and distance to the scattering target, there are different types of signals. The modulation function depends on the reflecting property of the target (which varies the amount of feedback) and on the distance to the target. This parameter provides information about the surface properties for solid targets and density for fluids.

The velocity can be directly calculated from (1) by differentiating the signal. The velocity signal can be considered as the result of mixing the lasing field within the LD cavity and the Doppler-shifted backscattered light. If the target has the constant velocity $\boldsymbol{V}$, then the Doppler shift of the periodic optical power fluctuation is equal to

$$\mathrm{f} = 2\frac{(V, n)}{\lambda} \,, \qquad (2)$$

where $\boldsymbol{n}$ is the unit vector in the direction in which the harmonic wave of light moves, and λ is the wavelength of the laser light. However, as soon as the target surface shows a non-uniform surface, the speckle effect will occur. For instance, assuming that the incident light has a 0.65 μm wavelength, and the roughness of white paper is of the order of 1 μm, the coherence length of the reflected signal decreases, and speckle effects will create additional noise in the signal. When a spectrum is then calculated by fast Fourier transformation (FFT) additional algorithms need to be used to suppress speckles and other noise.

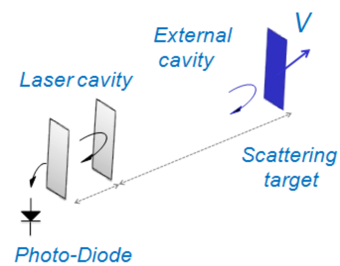

Figure 1: Illustration of the SM system with an external mirror as a target.

Self-Mixing Velocimeter Design

SM technique can be used with any kind of laser as long as the properties of the laser are correctly taken into account in the equations for the electric field and carrier density. In the case of a supersonic gas jet, LD is going to be used. Such system can be compact, easily integrated into an existing set-up and is very cheap. In addition, SM does not need any additional complex optics components.

The full velocimeter consists of LD, photodiode (PD) for the monitoring of the signal, a signal amplifier, and some optical components for light collection in case of low levels of scattered light.

In the actual set-up, there will be distance between the gas-jet and the LD of about 10-20 cm. According to (2) the angle between the laser axis and the gas-jet axis should be non-zero to get a signal with Doppler shift. Moreover, depending on the angle, different Doppler shifts and hence precisions can be achieved in the experiment. It is important to investigate into these parameters and to find the optimum combination of them. For this aim, experiments with solid targets were performed with results presented in the next section. Preliminary calculations based on the expected properties of the gas jet showed that the amount of scattered light from the jet might not be intense enough to receive a good SM signal. If this was the case, the set-up could be changed for the purpose of jet characterization by adding seeders to the jet in order to increase the amount of scattered light. However, the principal design of the velocimeter-monitor would stay the same.

EXPERIMENTS WITH SOLID TARGETS

In order to test the SM method, experimental work was divided into several steps, including studies into different target objects. The first part of the experiments is to study the different regimes, which can be realized with the SM technique, and to change the distance between laser and target. The different regimes depend on the amount of light and hence directly pave the way to experiments with a gaseous target where a very weak feedback is expected.

In all measurements, an LD operating at 650 nm, type L650P007 was used, driven by a constant current. The signal is received from a build-in PD and amplified before signal processing. A lens is used for focusing the light onto the target, which was either highly reflective (mirror) or diffusive (white paper, or any other rough surface).

Two scenarios were considered for the experiment: First, the target moves in the direction of the laser axis, i.e. the distance is not fixed, and second, there is a fixed distance between laser and target. These initial experiments are important for adjusting the system and optimizing the signal. The main steps of the optimization process are noise reduction, focusing/defocusing properties of the laser light, distance, etc. The second scenario with a fixed distance is very close to the experiment with a gaseous target, and it is important for finding the correct position of all components of the system. If the target moves with a fixed and well-known velocity it can be used as for checking and calibrating the velocimeter.

Target with High Reflectivity (Mirror)

In first experiments the main goal was to investigate ways to receive the right type of signal and how to improve its quality and amplitude. It was found that in order to receive a proper signal, many different things need to be optimized, such as distance to the target, noise in the diode, noise in the amplifier, and optimized collimation. In the regime of weak feedback a neat phase transition and a linear decay following it should be achieved. As a result, the measured SM signal became close to the theoretically expected one, see Fig. 2a.

The next part of the study was to derive the velocity of a movable stage from SM measurements. The linear transformation stage M-403.xVP driven by DC Motor Controller C-863 is supposed to move with rather precise and constant velocities, which can be controlled remotely. Velocities can be modified between 0-10 mm/s with a movement range between (0-100) mm. The distance between the LD and the mirror was varied between 10 cm and 50 cm. In each case, different velocities were considered. For the calculation of the velocity, a signal processing software was written which allows to calculate the velocity of the signal with an accuracy that mainly depends on noises and system instabilities. The signal beats on the Doppler shift frequency which is proportional to the velocity according to (2). The program for calculating the spectrum was based on FFT with different windows, and fitting the peaks afterwards together with calculating the velocity.

Typical results are shown in Table 1 for the mirror as target. The reflectivity of the mirror is 95 % at a wavelength of 650 nm. It can be seen that the accuracy is increasing with distance between target and LD. This is due to a reduction in the feedback strength and shows where the SM signal has the best operation regime. In our measurements, we found that velocities can be detected with accuracies of better than 1.5%.

Table 1: Main Results of the Experiments with a Mirror as Target; 95% Reflectivity at 650 nm

Distance between the target and LD, cm	**Defined velocity, mm/s**	**Accuracy, %**
20	5	1.1
30	5	0.7
40	5	0.9
50	5	0.5
20	10	1.0
30	10	0.5
40	10	0.8
50	10	1.4

Target with Diffusive Reflectivity (White Paper)

After having received good results with the mirror target, the same experiments were done with white paper. White paper is a target which scatters the light strongly. In this case, alignment is not the most critical point. The amount of light which goes back into the laser cavity depends on how much the light will be focused/defocused on the target. The stronger the light is focused on the target, the better the results.

One example of a signal from white paper is shown in Fig. 2b. In a first step the experiments were done in an identical configuration as with the mirror. The accuracy of the velocity measurement in this case was better than 1.5%. Typical results with white paper as target are shown in Table 2. The accuracy of the result is much better when the target is closer to the LD as more light is reflected back into it. The reflectivity of white paper is 60% for 650 nm.

As a next step, measurements were carried out so that the normal vector of the white paper surface had non-zero angle. In this case, the reflectivity of white paper does not influence the amount of feedback from the target. However, the character of the signal has not changed, and the results of the measurement were the same. This is due to the scattering phase function of white paper which is proportional to the cosine of the angle and has a forward character.

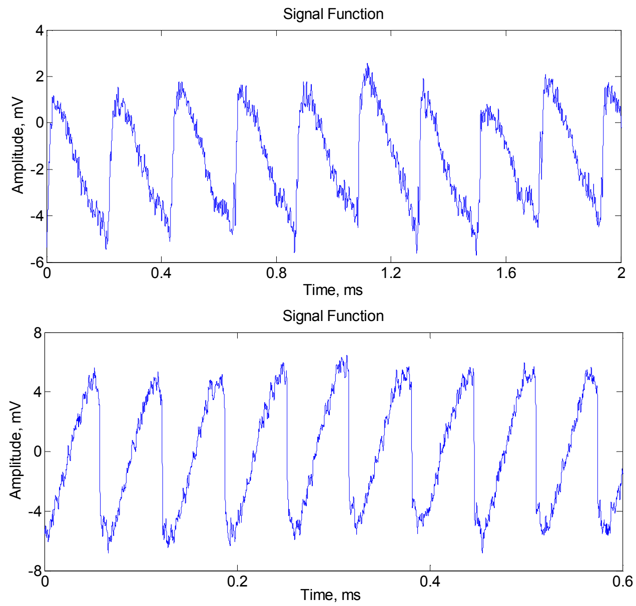

Figure 2: Example of the signal received from SM (a) with a mirror as target (b) with white paper as target.

Table 2: Main Results of the Experiments White Paper as a Target (60% Reflectance for 650 nm).

Distance between the target and LD, cm	Defined velocity, mm/s	Accuracy, %
10	5	0.9
20	5	0.8
25	5	1.3
30	5	1.4
10	10	0.3
20	10	0.5
25	10	1.2
30	10	1.4

OUTLOOK

In the case of a supersonic gas jet, various challenges still need to be addressed, such as the geometry of the velocimeter, the possibility of detecting an object with a very high intrinsic velocity, and a low level of scattered light. A gaseous target will scatter the light in a different way than a solid target. It is thus important to carry out experiments with a target of similar nature to identify the best geometry configuration, to try different types of seeders in case of low levels of scattered light, and to check possible limits of such system. The high velocities of the supersonic jet produce additional phenomena inside the gas jet which should be considered beforehand as well. Such experiments are planned to be performed with both, fluid and gaseous targets. Moreover, the envisaged density profile measurements can only be done with gaseous and liquid targets.

In order to study the limits of the system in terms of velocities, experiments with a rotating disc are going to be carried out, where the angle of incidence and the velocity of the target for fixed distances between LD and target can be studied.

CONCLUSION

First results from investigations into a velocimetry based on laser self-mixing for the characterization of supersonic gas jets as used in advanced beam profile monitors were presented. The preliminary design of such monitor based on a LD and the SM technique shows good potential for a compact and cost efficient experimental setup. This shall be used for an accurate characterization of the gas jet, probing simultaneously its density and velocity. Laboratory experiments with different solid targets with varying reflectivity showed the possibility to measure velocities with better than 2% accuracy.

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