Recent Advances in Self-Mixing Laser-Doppler Velocimetry: Use as a In-Vivo Blood Flow Meter.

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ABSTRACT

In the present paper, recent experimental advances obtained with a laser Doppler self-mixing velocimeter are reported. The self-mixing effect in a semiconductor laser is used to realise the velocimeter. The velocity is calculated measuring the frequency peak of the frequency spectrum of the intensity signal generated by the laser diode when modulated by feedback light coming from the moving scattering particles. A special optical fiber version of this velocimeter to be used specifically for intra-arterial blood velocity measurement has been realised and a solution for reducing temperature influence on the semiconductor performances is proposed. The results of the in-vivo tests carried out with the proposed sensor are presented.

Keywords: Self-mixing, laser Doppler velocimetry, blood flowmetry.

1. INTRODUCTION

The increase of interest in the study of non-contact, non-invasive measurement techniques in the different fields of science can be explained mainly by the great advantages that such techniques can give in the experimental determination of physical characteristics, such as: velocity, displacement and acceleration. In many cases the application of the sensor body on the object under test can introduce a modification of the measurement conditions. In certain conditions, it is impossible to perform the measurement with a contact sensor. Especially in the field of biomedical measurements the necessity of avoiding any contact with the object of measure is of main importance. For example the measurement of vibration of small dimensions bodies as human teeth can not be carried out using classical accelerometers, because of their dimensions and weight, in [1,2], Castellini et al. have performed displacement and velocity measurements of human teeth natural vibration frequencies using a laser Doppler vibrometer. Another important field of application is the measurement of blood velocities. Blood flow characteristics can, in fact, be used to monitor arteries and veins health conditions. Eventual reduction or modification of normal flow state inside an artery or a vein is an important diagnosis factor of circulatory disorders.

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At present, the only way to check the blood flow is to place an ultrasonic or electromagnetic sensor directly onto the artery checked point. This results in a very invasive procedure. In fact, it is necessary to create an access to the measurement point to insert the sensor, and for some ultrasonic sensors, it is even necessary to fill the measurement area with homogenous fluid. Therefore, the overall procedure results in very much invasive and is performed rarely.

In this work, authors propose a new procedure to measure the blood flow and velocity directly inside the artery or vein, reducing at minimum the invasivity of the measurement procedure. The proposed technique has been designed to optically perform the measurement of the blood cell velocity directly inside the artery by means of a small optical fiber (few μm of diameter). The sensor can be moved up and down the artery, allowing a series of multiple measurements and characterising the blood velocity (and consequently the blood flow) along the artery. The fiber is moved inside the artery by means of a special catheter that can be easily inserted even far from the measurement point. The proposed technique has been designed to be easily integrated with the surgery procedures aiming to optimise artery flow conditions when pathological obstruction are present. The sensor here proposed is based on the self-mixing effect [1 - 5] present in a laser diode cavity when the back-reflected light coming from a moving target and transmitted by the optical fiber is reintroduced into the laser diode cavity [6]. The two waves are characterised by slightly different frequencies because of the Doppler shift affecting the reflected one [7]. The built-in photodiode present in most of the commercial laser diode can be used to convert the light intensity fluctuation present inside the cavity into an electrical signal. This signal is characterised by a frequency equal to the Doppler frequency therefore its frequency is proportional to the velocity of the moving target. Different versions for laser Doppler velocimeters have been presented in the past [7] and some commercial systems are already available. But the diffusion of sensors based on Doppler though of great interest, is still not complete because the high costs of such systems, their large dimensions and the need of expert technicians to be used.

The self-mixing base sensor hereafter proposed aim to solve these disadvantages. In fact, the optical head, aimed to generate the interference, and the photodiode to generate the electric signal are confined into the same laser diode cavity. This allows to realise a very small and very light sensor (few millimetres of diameter and few milligrams of weight), especially if compared to the commercial laser Doppler velocimeters. Some others advantages of this kind of sensor lie in the easy alignment of the set-up, the relatively comfortable signal-to-noise ratio and the low costs of the apparatus. Thus multiplexed measurements with a set of instruments combined with one signal processing system are feasible, and correlations between different measuring positions can be easily made. Solutions to some of the main disadvantages of this method, such as optical instabilities and local disturbance of velocity pattern by the fiber tip have been discussed in [8].

The present paper will present the experimental results obtained using the self-mixing laser Doppler velocimeter sensor for the realisation of a blood flow in a series of in-vivo tests. The used sensor is an updated version of the first prototype laser Doppler self mixing velocimeter presented by de Mul et al. [4, 6, 8 - 10].

The research has been carried out at the Department of Applied Physics of the University of Twente and at the Department of Mechanics of the University of Ancona.
2. EXPERIMENTAL SET-UP AND MEASURING PROCEDURE.

In figure 2.1 it is reported the experimental set-up utilised for the realisation of the self-mixing laser Doppler velocimeter. It is composed of a 9-mm diameter laser diode, coupled to a 0.5 mm diameter optical fiber. The Doppler frequency is measured by observing the frequency spectra of the built-in laser diode photodiode. This photodiode, being placed close to the back diode cavity, follows the intensity fluctuations of the laser diode due to the interference effect caused to the slight difference of frequency between the cavity mode and the back-reflected light.

![Figure 2.1. Laser Doppler self-mixing velocimeter.](image-url)

A GaAlAs laser diode has been used in the set-up. It is a Philips CQL47A/D2 emitting at 825 nm, with a maximum output power of 12 mW. Inside the laser diode package a photodiode is present to monitor the laser output from the back facet of the laser diode. We have used this signal to pick-up the self-mixing signal generating inside the cavity [4,6]. The interference signal from the photodiode is amplified by an amplification stage (Tektronics, AD 1 MHz) before to be sent to the spectrum analyser in order to obtain sufficiently high signal. The spectrum analyser is an Hewlett-Packard HP3589A. The laser diode cavity is driven by a stabilised current source (ThorLabs, LDC 500), able to generate current for the diode cavity from 0 up to 500 mA, with an accuracy of ± 0.2 mA. In order to control the laser diode temperature, a temperature stabilisation circuit (ThorLabs, TEC 2000) together with a laser diode thermo-electric cooler (ThorLabs, TCLDM9) has...
been used. The temperature can be set with a precision of ± 0.1 °C in the laser diode working range. In this way unexpected mode hopping effect can be avoided.

The optical part of the experimental set-up consists of a spherical cd lens (Philips AO54, f=4.4 mm, NA= 0.46) to obtain a parallel beam, and a microscope objective (Olympus MD Plan X10, NA= 0.25) for launching the light into the optical fiber (3M, core 200 μm ± 5 μm, cladding 225 μm ± 5 μm, NA = 0.39 ). The typical coupling efficiencies were of 65 – 70 %. The fiber length was about 1.5 m.

The optical fiber was introduced into the iliac artery of a 35 – 40 Kg animal, by means of a basket catheter (figure 2.2). This catheter has been placed upstream, about 4 cm after the femoral arteries bifurcation. In order to maintain a stable position along the artery, a multifilament memory wire basket has been opened inside the artery. Once the basket has been opened the optical fiber can be moved out the catheter to start the measurement. In figure 2.3, the catheter tip is reported with the basket opened. In the same photo, it has been highlighted the optical fiber in the measuring position as it is when it is working into the artery.

![Diagram of catheter and artery](image-url)

Figure 2.2. The measurement position and the basket catheter (iliac artery).
3. **IN-VIVO MEASUREMENTS.**

The experimental data have been collected using the set-up reported in paragraph 2, following the procedure presented in paragraph 3. A typical spectrum measured after having positioned the catheter from the left femoral artery is reported in figure 3.1. In the figure, the average of 100 spectra is reported. For this measurement, the catheter has been positioned in the centre of the artery and the position of the fiber has been held using the basket. The angle between the direction of the blood flow and the fiber optical axis is in between 0 and 30° degree, and it has been verified before the starting of the measuring procedure, using a X-ray viewer able to identify a radiopaque plaque fixed on the catheter tip. In the same figure it has been reported the spectra measured after having caused a temporary artificial occlusion of the artery. The measurement has been taken following the same procedure used in the normal flow condition measurement.

In figure 3.2, the difference between the two spectra has been reported. In this graph it is possible to individuate the cut-off frequency (400 kHz), which correspond to an average blood velocity of about 16 cm/s. The blood flow measured by the reference blood flowmeter was 0.7 l/min in the normal flow condition and a very low flow (under 0.1 l/min) during the occlusion. It was not possible to create and maintain a state of total occlusion for long period of time in order to not compromise the health state of the animal. Observing the spectral difference, reported in figure 3.2, it is possible to observe the presence of some spectra “drop down” both in the 0 – 400 kHz band, and in the 400 kHz 1000 kHz band. We believe that these reduction of the differences to low values can be caused by the blood cells coagulating over the fiber tip, by the low number of averages and by the non perfect occlusion conditions.
Figure 3.1. Upstream frequency spectra (flow/no flow conditions).

Figure 3.2. Difference of the spectra (flow and no flow conditions).
A second experiment was carried out measuring the spectra relative to two different positions of the optical fiber, respect to the catheter. The catheter was placed upstream, inside the artery, and its position was hold opening the basket. Its orientation (angle between fiber optical axis and artery walls) was verified by the X-ray viewer. The two spectra reported in figure 3.3, are relative to two measurements: the first one was carried out leaving the fiber inside the catheter, therefore with no flow, the second one was carried out positioning the glass fiber 2 cm outside the catheter tip, as it is reported in figure 2.2. The two spectra was measured averaging over 200 spectra. In figure 3.4, the difference between the two spectra is reported. A cut-off frequency can be individuated at 400 kHz (average blood velocity 16 cm/s). In this case the difference of the spectra does not present any “drop out” of the signal and this can be due to the higher number of averages respect to the previous experiment. All the tests have been conducted after having placed a reference instrument for the determination of the effective blood flow (commercial transonic flowmeter with an accuracy of 5%). It is therefore possible to compare the average blood velocity derived from the transonic flowmeter data with the ones measured with the self-mixing laser Doppler velocimeter. In figure 3.5, it is reported the comparison of the measured velocities. The velocities have been reported in function of the artery internal diameter. The real value of the internal diameter of the iliac artery was measured at the end of the tests, in absence of blood flow. The value measured was of about 14 mm. The measurement of the artery diameter was performed measuring its section, therefore in absence of blood pressure. We have estimated a dilatation of 0.5 mm due to the blood pressure. The velocity derived from the transonic flowmeter is reported highlighting the 5% accuracy bar. In the same graph, the self-mixing measured velocity is reported for two different values (0° and 30°) of the angle between the optical axes of the optical fiber and the artery walls. It is possible to notice that for values of internal artery diameter of 14.5 mm, there is a good agreement between the velocities derived from the measurements performed by the reference flowmeter and the values measured by the self-mixing laser Doppler velocimeter.

![Figure 3.3. Spectra measured with glass fiber inside and outside the catheter.](image-url)
Figure 3.4. Difference of the spectra measured with the glass fiber inside and outside the catheter.

Figure 3.5. Comparison between blood velocity: reference instrument (transonic flowmeter, with accuracy of 5% and self-mixing laser Doppler velocimeter)
4. DISCUSSION AND CONCLUSION

In this contribution, authors report on the realisation of a self-mixing laser Doppler blood velocimeter. The device has been realised on a special version using an optical fiber and it has been integrated with a basket catheter to be used directly into the artery. The basket allows to locate the optical fiber in the desired position, maintaining it during the measurement time. A special temperature controlled laser diode mount has been used to reduce optical instabilities due to temperature effect on the laser cavity. The self-mixing laser Doppler velocimeter has been tested on an in-vivo experiment as a blood flowmeter and the measurement data have been compared with the measurement performed with an ultrasonic commercial flowmeter. Good agreement with data measured with this reference instrument has been obtained.

Some problems still have to been resolved to optimise the procedure. Blood cells covering of the optical fiber tip, can "obscure" the sensor, therefore anticoagulating drugs have to be used. The precise measurement of the internal artery diameter is not easy and can be only estimated causing uncertainty on the flow value calculated from the velocity measurement.

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REFERENCES
