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Optical Feedback Interferometry sensor for flow characterization inside ex-vivo vessel

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Abstract—Pressure myograph systems allow the study of pharmacological effects of drugs and other vasoactive compounds on small isolated vessels by image processing. In this work, we present a new pressure myograph system based on Optical Feedback Interferometry (OFI) sensor that gives information about local velocity in fluids and enables reconstruction of a velocity profile inside a vessel.

OFI is a self-aligned interferometric technique that uses the laser as both the light source and the receiver thus offering high sensitivity, fast response, and a simple and compact optical design. The local Doppler flow velocity is directly measured inside ex-vivo rat vessel with a step of 100 μm thus avoiding the need to use complex image processing and models based profile calculation for extracting flow velocity. This technique will be useful to investigate hemodynamics in microcirculation by measuring unsteady irregular blood.

I. INTRODUCTION

The need to accurately measure physiological functions and properties of small arteries, veins and other vessels is well established [1]. Vascular smooth muscle cells, located inside vessel wall play a key role in contraction and relaxation of arteries [2].

These vasoconstriction and conversely vasodilatation effects are driven, in normal conditions by the central nervous system or, in case of disease, by vasodilative or vasoconstrictive drugs. In the perspective of vessel characterization, two kind of measure systems exist:

- The isometric method, which measures changes in force from dissected resistance arteries while the length (diameter) remains constant.
- The isobaric method, which measures changes in diameter while transmural pressure across the artery wall is kept constant.

This paper will be focused on isobaric or pressure myograph systems. On these sensors, a single vessel is isolated on two glass cannulas, pressurized and flushed by a liquid to simulate blood flow [3]. Then, the artery is imaged on a video monitor and diameter is assessed by contrast detection of the arterial wall in the dimension analyzer. Investigation on myogenic response, vasodilative effect and endothelium behavior can be done with this kind of system [4].

In our sensor, the vessel cannulation set up is inspired from myograph systems but instead of using high resolution camera and microscope sensors, OFI is employed.

In the OFI process, the light emitted from a laser source is backscattered from a moving target and re-enters in the laser cavity. This optical feedback produces a modulation of the optical output power. At the micro scale, the maximum Doppler frequency of the interferometric signal and the relative flow velocity are correlated [5].

For biomedical sensing, OFI sensors are ideally suited for measurements of blood flow: local flow in rat brain [6] or extra corporal circulation ([7], [8]). By moving the sensor across a microfluidic channel, Campagnolo et al. ([5]) provide a system able to measure parabolic profile of velocity inside a capillarity tube.

This study proposes a new sensor for myograph systems able to measure local flow velocity with a 100 μm step and, by scanning a whole vessel section, a flow profile is extracted. Internal vessel diameter is estimated from the profile base width and a 2D vessel velocity image is computed.

II. MATERIALS AND METHODS

A. OFI theory

The more generalized sensing method used in laser diodes is the measurement of the optical power changes in the photodiode (PD) due to optical feedback induced by scattering targets. The relation of the emission power with target velocity is given by the formula:

$$P_T = P_0 \left[1 + \cos \left(2\pi \frac{2(L + V_T t)}{c} \right) \right] \quad (1)$$

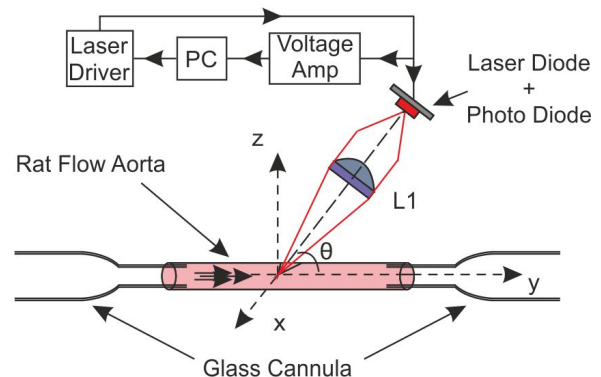


Fig. 1. OFI Sensor setup for internal rat aorta diameter assesment

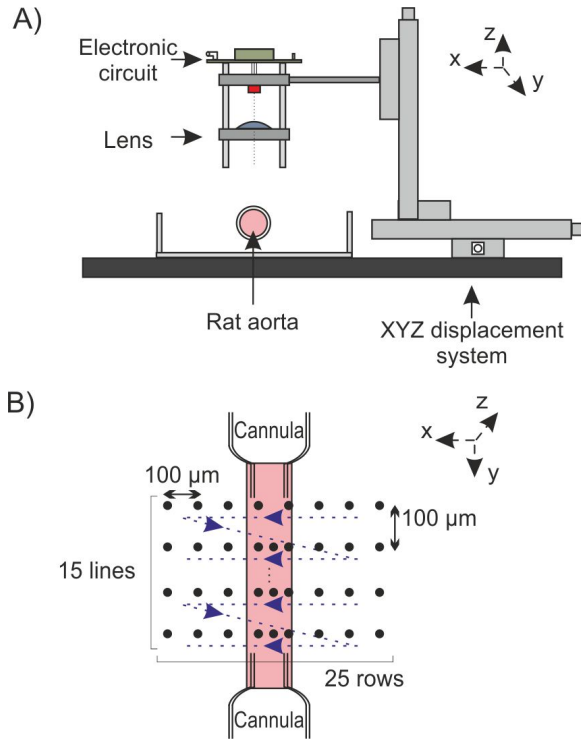


Fig. 2. OFI sensor: A) Lateral view, B) Top view of the aorta scanning

where P_0 is the optical power of the laser without feedback, L is the distance between the target and the laser, c is the speed of light, t is time and V_T is the target velocity.

OFI sensors are well suited as alternative optofluidic systems as long as there is a minimal concentration of particles embedded in the fluid acting as scatterers. OFI signals from fluid flow contain information on particles velocity in the fluid in a wide range. The power spectral density analysis of the Fast Fourier Transformation (FFT) of temporal signals allows the direct calculation of flow velocity, which is related to the fundamental Doppler frequency $F_{Dopplermax}$ in the spectrum as follows:

$$V_T = \frac{\lambda * F_{Dopplermax}}{2 * \eta * \cos(\theta)}. \quad (2)$$

where η is the refractive index of the liquid flushed, θ the angle between the laser and the flow direction and λ the laser wavelength.

B. Aorta preparation

From frozen Wistar rat, carotid aorta is extracted and cannulated on two glass cannulas. At both extremities, the aorta is held in place with two sutures (5-0 USP).

It is then pressurized and flushed by a liquid composed by a ratio of 10:1 of Phosphate Buffered Solution and milk. The speed flow and pressure are considered as constant during all the experiment because of the use of a high precision pressure pump (Fluigent MFCS-EZ-4C). The laser sensor is focalized on the center of the vessel where the Doppler frequency reaches its maximum (figure 1).

C. OFI Sensor signal recording

Figure 2.A shows an overview of OFI sensor used for this study. It is composed by three main parts:

- XYZ displacement system. Three miniature motorized linear stages (Zaber-LSM 50A) move the laser with a resolution of $0.1905 \mu\text{m}$ and are controlled by computer.
- One plano-convex optical len (LA1951-B).
- A compact electronic system that realizes both laser driving and signal amplification functions. The prototype fits on a $5 \times 5 \text{ cm}$ PCB.

The amplified photodiode signal is digitized by a National Instruments card (NI USB 6251) connected by USB to a computer. For each measurement point 4096 samples are recorded at a frequency of 1MHz.

The optical setup consists on a laser diode (HITACHI HL7851G) emitting at 785 nm and driven by an injection current of 50 mA. The laser is coupled to a single lens of 25.4 mm focal length and the collimated radiation is pointed to the vessel with angle of 86° .

The 2D automatic scanning protocol is presented in figure 2.B. The scan mechanical system and laser's photodetector signal recording are synchronized using Labview VI. For one position, 10 succesively temporal signals are recorded and processed off-line using a Matlab script/code. The fundamental Doppler frequency provides the information necessary to calculate the local velocity according to equation 2, thus kinematic properties of the flow can be easily determinated.

Because of the size of a rat aorta is between $500 \mu\text{m}$ and 1 mm , we have selected a scan step of $100 \mu\text{m}$ which is also analog to the resolution of the camera. For each position, the

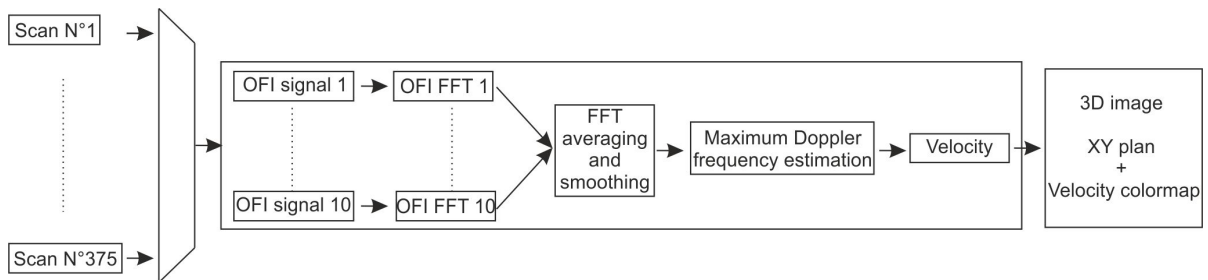


Fig. 3. Overview of the computational process, from OFI signal to 2D velocity mapping

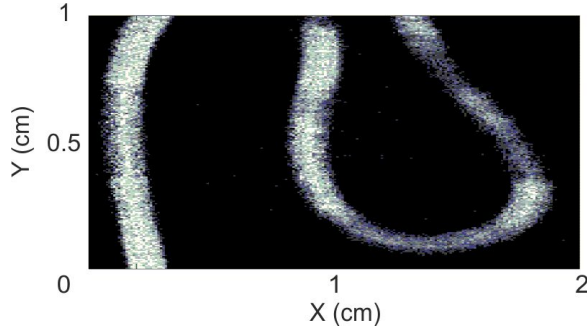


Fig. 4. 2D velocity mapping on a fluidic device

OFI sensor records 10 measurement points in order to make a FFT average. At the end of the recording process, each position data are stored in a text file with 40960 samples (4096 samples \times 10 records). For an aorta scanning area of 3.75 mm^2 , 10 minutes and 160 Mb of memory are required.

D. OFI Sensor signal processing

In [5], the signal processing consisted in the fitting of the OFI signal spectrum by a complex exponential function.

This method, despite the excellent results obtained for the estimation of the fluid velocity, was requiring a rough calibration of several coefficients in the fitting function before running the fitting algorithm itself. Thus it was not possible to run the signal processing for the full scan in an automated way.

The signal processing approach have been changed and, by setting a threshold level in the electrical spectrum of the OFI signal, the maximum Doppler frequency is evaluated.

The signal processing block for one position is presented in figure 3. For each position, 10 FFTs of the photodiode signal are computed, averaged and smoothed. The maximum Doppler ($F_{Dopplermax}$) is extracted by spectrum thresholding and, according to equation 2, maximum velocity (V_T) is measured.

Figure 4 shows an example of a 2D velocity mapping on a plastic tube ($500 \mu\text{m}$ internal diameter), with a $10 \mu\text{m}$ scanning step on an area of 2 cm^2 .

III. RESULTS

A. Image processing diameter assessment

From the literature, internal Wistar rat carotid have been evaluating around $850 \mu\text{m}$ [2]. Figure 5 shows a 220×182 pixels picture of the cannulated and prezurised carotid aorta. One pixel correspond to $100 \mu\text{m}$ and internal diameter is evaluated by taking suture thread as reference. In that context, after an image processing, the internal diameter have been computed in between $800 \mu\text{m}$ and $900 \mu\text{m}$.

B. OFI diameter assessment

1) *Sensor calibration:* For the first use, a calibration procedure has to be done prior to aorta extraction. Indeed, because of the optical setup, the laser beam position is unknown and has to be focus in the middle of the channel.

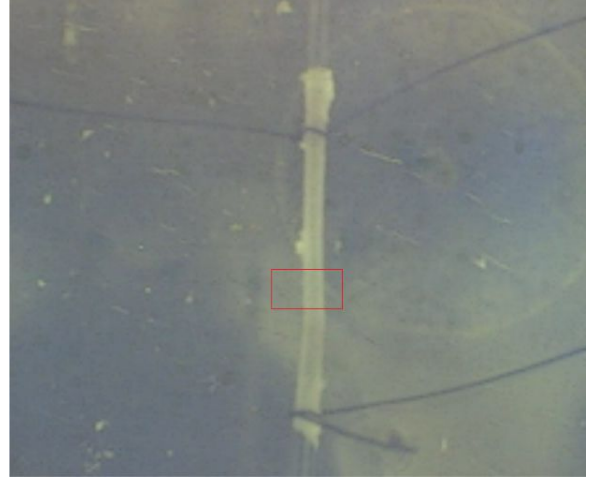


Fig. 5. Cannulated rat aorta: Red rectangle corresponds to OFI scanned area

In that perspective, a calibration scan is done on a well known diameter tube and fluid. The sensor is calibrated with a solution of milk (1%) and distilled water (99%) flushed inside a plastic tube at a constant velocity. Then, the beam is manually adjusted along the three axis and θ angle where the OFI signal reaches its highest frequency.

When the middle of the channel is found, a scan is performed and base velocity profile width is evaluated. Then the result is compared to the tube diameter in order to determine the threshold level. In this study, the threshold is set to 14 dB.

2) *Aorta 2D imaging:* Before scanning, the laser beam is focused on the centre of the aorta in the same way for the calibration procedure. Then it is moved towards the x axis through the scan start point. As soon as the fluid velocity is stabilized the complete 2D laser scan is performed on a surface of 3.75 mm^2 . In figure 5, the red rectangle represents the scan zone with a width of 2.5 mm (x axis) and a height of 1.5 mm (y axis). For each scan line (along x axis), an aorta OFI fluid velocity profile is computed from the maximum Doppler frequency extracted from spectra.

Figure 6 presents results from one line scan where three points of interest have been highlighted (outside aorta (black), $300 \mu\text{m}$ (red) and $500 \mu\text{m}$ (purple) inside the aorta). FFT spectra of these points are shown in figure 6.A and fluid velocity profile in figure 6.B. On a first hand we can notice a difference between spectrum outside the aorta (black curve) and inside (red and purple curves). In a second hand, despite the fact that there are $200 \mu\text{m}$ between the two positions, maximum Doppler frequencies are well distinguish.

The fluid velocity profile (figure 6.B) is composed by 25 measurements points and from the base profile width, an aorta diameter of $850 \mu\text{m}$ is measured. Moreover, Poiseuille' law describes the fluid velocity profile inside a tube as parabolic [5]. Even without any fitting, from the experimentally measured flow velocity profile plotted in figure 6.B, a parabolic shape is observed. The complete aorta scan and the comparison with the raw image is presented in figure 7. From the OFI sensor image, the aorta is clearly visible and the fluid velocity distribution can be analyzed. High speed flow (between 0.7 and 1 normalized speed) is observed on $300 \mu\text{m}$ in the middle of the aorta. Near

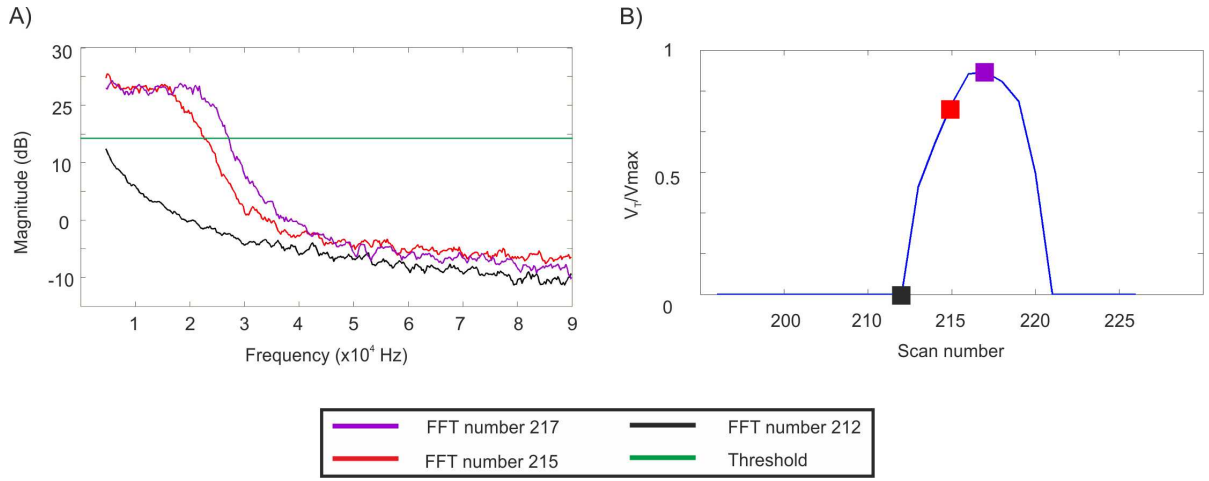


Fig. 6. One line scan on rat aorta by OFI: A) Three FFT spectra: outside the aorta (black), 300 μm (red) and 500 μm (purple) inside the aorta, B) Fluid velocity profile composed by 25 scan points

aorta walls, velocity decreases drastically due to the absence of particles. OFI sensor can provide with high precision the localization of aorta walls.

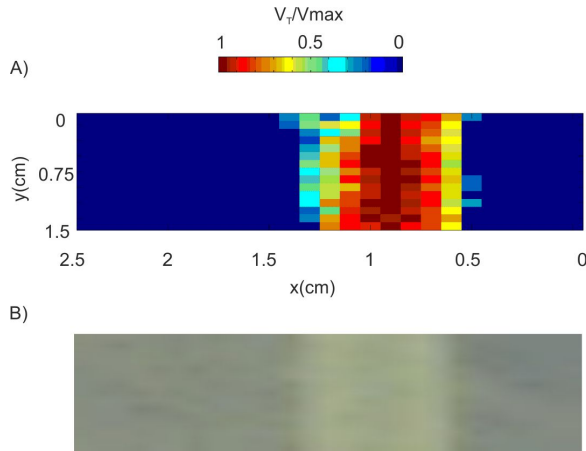


Fig. 7. Rat aorta imaging: A) 2D rat aorta fluid velocity imaging captured by OFI and B) Raw image of the scanning zone captured by camera

IV. CONCLUSION

The feasibility to use an OFI sensor for flow characterization inside ex-vivo rat aorta has been demonstrated. Two main informations are provided: internal vessel diameter is estimated from the profile base width and local velocity information is extracted from the correlation between OFI signal and position. Because OFI sensor is based on basic signal processing methods, electronics and optics, it differs from the well establish technology. In addition, with this sensor coupled to myograph systems, the investigation on hemodynamics in microcirculation by measuring unsteady irregular blood is now a reality for biomedical field and medicine.

In this study, a 100 μm scan step has been used. By accepting a compromise between precision and recording time, we will reduce this scan step to 10 μm in order to provide a high definition fluid velocity image. In that perspective, future works on OFI sensors will be focused on the mechanical

displacement system. Indeed, the scanning protocol is time consuming: on 600 seconds dedicated to the scanning, only 2 % of the time is used for OFI signal acquisition and recording. The time remaining is consumed by the mechanical system. Due to this main drawback, new displacement systems based on mirrors or continuous scanning will be further developed in our future OFI sensors.

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