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A simple and robust optical scheme for self-mixing
low-coherence flowmeters

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ABSTRACT

The developed measuring system is based on a low-coherence source and a self-mixing (or internal) detection. The proposed optical layout exploits the reflection from the internal wall of the duct as reference arm, thus reducing system complexity, cost, size and increasing its robustness to movements of the measurand. Moreover, the usage of a low-coherence source allows reducing the problems related to the poor definition of the volume under test (sensing region or measurement volume) typical of “coherent” self-mixing systems. Although preliminary analysis have been performed by simply investigating the frequencies relative to the maximum in the Doppler spectrum, the obtained results demonstrates that by increasing scatterers concentration of +300%, the system sensitivity increases of about only +20%.

Keywords: Low-coherence interferometry, Flowmetry, Self-Mixing, Biological tissues, Turbid medium.

1. INTRODUCTION

Laser Doppler velocimetry (LDV) is a well-known and widely used measurement technique. Nowadays, it is one of the preferred techniques to obtaining accurate, non-intrusive measurements of fluid or particle velocity. Moreover, the achievable non-invasiveness and the ability to manage hostile environments, have been really appreciated both in biomedical and industrial fields. However, when the fluid is turbid or the duct is buried in a turbid medium, e.g. a blood vessel, multiple-scattering regime sets in, thus techniques based on coherent sources are known to suffer great uncertainty. Unfortunately, this is a quite typical situation in many biological tissues where photons usually migrate along random pathways from the transmitting to the receiving optics.

Low-coherence illumination can be used to overcome this limitation. As an example, Doppler optical coherence tomography (DOCT) allows to measure flow-velocity profiles either in the case of highly scattering fluids or when the duct is buried in a turbid medium. Despite the advantages offered by LDV and DOCT systems, some drawbacks, e.g. complexity and costs, limit the field of applications. System complexity and cost can be significantly reduced by exploiting the self-mixing (SM) approach.

The SM technique requires that a portion of the light emitted by the source is backscattered from the moving scatterers and re-enters the source cavity where it causes measurable changes

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in emitted power. The resulting output-power fluctuations are then measured by using the back-facet monitor photodiode (PD).

The SM technique is widely used in conjunction with coherent light sources. As an example, in recent years we proposed some SM-LDV systems aimed at estimating blood flow both in extracorporeal circulation and, in the ocular fundus. However, in SM systems the same optic acts as both illumination and collection optics, thus the volume under test (VUT) is not sharply defined as in classic LDV systems where the intersection of the illumination and collection optics defines a small and precise volume. As a result, in LDV-SM the shape of the Doppler spectrum depends on the scattering coefficient of the sample, thus the measurement uncertainty suffers from variations in scatterers concentration e.g. due to variation in the blood hematocrit.

The use of low-coherence sources allows better defining the VUT, thus reducing the effects due to variations in scatterers concentration. Nevertheless, in spite of the simplicity of the SM technique, classical optical layouts for low-coherence sources usually require a reference arm to set the VUT, thus limiting the potential advantages of the SM techniques, increasing the complexity of the system and reducing its robustness.

In this paper we propose an optical scheme that exploits the reflection from the inner wall of the duct as a reference arm. Such solution highly simplify the optics and greatly reduce the problems related to movements of the reference arm and/or the measurand.

The developed system is a modified version of the system that we have previously described. After a brief review of the theoretical background reported in subsection 2.1, subsection 2.2 describes both the proposed optical layout and, the expected interferometric signal. The developed measuring system and the used experimental setup are shown in subsubsection 2.3 and 2.4, respectively. Finally, preliminary measurements demonstrating the applicability of the proposed measurement system are reported in section 3 and discussed in section 4.

2. MATERIALS AND METHODS

2.1 Theoretical Background

In interferometric systems, two (or more) electric fields beat on a photodetector to reveal the relative field(s) phase differences. In particular, to reveal the Doppler shift generated by moving particles, interferometric systems generally split the probing beam into two parts. Then, according to the terminology introduced by Stevenson and Donati, two optical layout are usually exploited:

- **Differential Doppler Systems or Fringe Systems.** The obtained beams beat in the VUT, thus exposing the photodetector to the scattered light only.

- **Reference Beam Systems.** Only one beam illuminate the scatterers (measuring beam) and the beating between the scattered light and the other beam (the reference beam) occurs onto the photodetector active area.

Thus, what essentially interferometric systems are interested in is the interference effects arising on superposition of two fields.

Any Cartesian component of the field emitted by non-monochromatic sources may be described as the real part of the Fourier integral:

\[
\begin{align*}
  u(t) = \int_0^{+\infty} U(\omega) e^{-j(\phi(\omega)+\omega t)} \, d\omega,
\end{align*}
\] (1)
where $\omega$ is the angular frequency and $U(\omega)$ describes the emission spectra of the considered source.  

As a result, according to our previous article\textsuperscript{8} and supposing $K_1 \cdot u_1$ and $K_2 \cdot u_2$ to be the electric fields reaching the photodetector, the detected optical intensity is:\textsuperscript{11}

$$I = K_1 K_1^* (u_1(t-t_1)u_1^*(t-t_1)) + K_2 K_2^* (u_2(t-t_2)u_2^*(t-t_2)) + \ldots$$

$$+ K_1 K_2^* (u_1(t-t_1)u_2^*(t-t_2)) + K_2 K_1^* (u_2(t-t_2)u_1^*(t-t_1))$$

$$= |K_1|^2 I_1 + |K_2|^2 I_2 + 2 |\gamma_{12}(\tau)| \sqrt{|K_1|^2 I_1 |K_2|^2 I_2} \cos \arg \gamma_{12}(\tau),$$

(2)

where $\tau = t_2 - t_1$; the terms $|K_1|^2 I_1$ is the intensity which would be observed from the field $K_1 \cdot u_1$ alone (similarly for $|K_2|^2 I_2$), and $\arg \gamma_{12}(\tau)$ is the arguments of $\gamma_{12}(\tau)$ the complex degree of coherence:\textsuperscript{11}

$$\gamma_{12}(\tau) = \frac{(u_1(t+\tau)u_2^*(t))}{\sqrt{I_1 I_2}}.$$

(3)

Supposing the light source to have a Gaussian line shape, according to the Wiener-Khintchine theorem the complex degree of coherence $\gamma_{12}(\tau)$ is expected to have a Gaussian shape,\textsuperscript{11,12} hence:

$$|\gamma_{12}(\tau)| = \gamma_0 \exp \left[ - \left( \frac{n_2 \cdot s_2 - n_1 \cdot s_1}{L_c^2 \ln 2} \right) \right],$$

(4)

where $\gamma_0$ is about equal to unit, $n_1$ and $(n_1 \cdot s_1)$ are respectively the refractive index and the optical path length of field 1 (similarly for field 2) and, $L_c$ is the coherence length of the light source.

### 2.2 Proposed Optical Layout and Expected Interferometric Signal

As shown in Figure 1, the proposed optical layout is based on the reference beam topology. In particular, the interferometric signal arises from the beating of the scattered field(s) and the field reflected by the internal wall of the duct.

Under the condition of weak feedback, the non-monochromatic light sources is virtually unperturbed by the back-diffused and reflected fields re-entering the active medium of the light source. Therefore, supposing that a single scatterer is imaged at a time, according to Figure 1 four electric fields impinge on the active area of the photodetector: (i) $K_0 u_0$ relative to the field emitted by the rear face of the light source (without optical feedback), (ii) $K_{R} u_{R}$ relative to the field reflected from the internal wall-surface of the duct (reference arm), (iii) $K_{S} u_{S}$ relative to the field scattered by the imaged scatterer and, (iv) $K_{RE} u_{RE}$ relative to the field reflected from the external wall-surface of the duct.

Since non-monochromatic sources have a coherence lengths $L_c$ of about few tens of microns, from (4) the only complex degree of coherence which can be different from zero is the $|\gamma_{RS}(\tau_{RS})|$ relative to the superposition of the $K_{R} u_{R}$ and the $K_{S} u_{S}$ fields. Hence, supposing $P$ to be the point of the internal wall-surface of the duct where specular reflection occurs, due to the roundtrip propagation, the VUT (imaged scatterers) is substantially composed by the scatterers whose distance from $P$ is lower or equal than $L_c/2$. As a result, if $N$ scatterers are simultaneously
Figure 1. Proposed optical layout. The “plane” non-monochromatic beam of light generated by the light source is directed at the air-duct interface at an angle of incidence $\theta$ (red arrow). Then, four electric fields are emitted, reflected or back-scattered toward the active area of the photodetector (black arrows): (i) $K_0 u_0$ relative to the field emitted by the rear face of the light source (without optical feedback), (ii) $K_{RS} u_R$ relative to the field reflected from the internal wall-surface of the duct (reference arm), (iii) $K_{RS} u_S$ relative to the field scattered by the imaged scatterer and, (iv) $K_{RE} u_{RE}$ relative to the field reflected from the external wall-surface of the duct. Obviously, only at normal incidence the optical rays associated with the reflected fields $K_{RS} u_R$ and $K_{RE} u_{RE}$ exactly retrace the optical axis of the light source. Nevertheless, thanks to the optics and the finite size of the reflected beams, part of the reflected beams can be collected by the system also for $\theta < 90^\circ$.

Imaged, neglecting the homodyne terms the detected optical intensity $I$ becomes:

$$I = |K_0|^2 I_0 + |K_{RS}|^2 I_{RS} + |K_{RE}|^2 I_{RE} + \sum_{i=1}^N |K_{S-i}|^2 I_{S-i} + \ldots$$

$$+ 2 \sum_{i=1}^N \sqrt{|K_{S,R}|^2 |K_{S,i}|^2 |K_{R}|^2} \cos[(2v_i \cdot t) \cdot k \cdot n],$$

where subscript $i$ refers to the $i^{th}$ imaged scatterers, $v_i$ is the velocity vector of the $i^{th}$ scatterer $k$ is the wavevector ($|k| = 2\pi/\lambda_0$, being $\lambda_0$ the center wavelength of the light source in vacuum) and, $n$ is the refractive index.

From (5) it is easy to observe that the current photogenerated by the monitor photodiode (PD) is composed by a DC component (first line of (5)) and, an AC component whose frequency band depends on the velocities $v_i$ of the imaged scatterers.

It is important to notice that from (5) each imaged scatterer give rise to a single frequency tone in the Doppler spectrum with frequency

$$f_D = \frac{2n v_i \cdot k}{2\pi} = 2n \frac{v_i \cdot \cos(\theta)}{\lambda_0},$$

where $v_i = |v_i|$ is the speed of the scatterer and, the second equality has been obtained supposing laminar flow — the particles velocities $v_i$ are tangential to the axis of the duct.

Therefore, the lower the angle of incidence $\theta$, the greater the sensitivity of the measuring system. Nevertheless, according to Figure 1 the lower the angle of incidence $\theta$, the lower the $K_{RS} u_R$ field reaching the photodetector. As a result, the geometry (angle of incidence $\theta$ and distance) has to be set as a trade-off between sensitivity and capability to collect the reference arm ($K_{RS} u_R$).
2.3 Measuring System and Data Analysis Technique

2.3.1 Measuring System

The developed measuring system consists of five macro-subsystems: (i) the non-monochromatic source, (ii) the driving electronics (DE), (iii) the signal conditioning electronics (SCE), (iv) the temperature controlled mount (TCM) and, (v) the thermoelectric temperature controller (TEC). As shown in Figure 2, the non-monochromatic source, a low cost superluminescent diode SLD (model 8414-04, Hamamatsu, Japan) was mounted inside the TCM (model TCLDM9, Thorlabs, USA). The SLD (model 8414-04, Hamamatsu, Japan) has a central wavelength $\lambda_0$ and a spectral bandwidth $\Delta\lambda$ of about 836 nm and 22 nm, respectively. Thus, we can estimate the coherence length in water, giving

$$L_c = \frac{0.44 \lambda_0^2}{n \Delta\lambda} \approx 11 \mu m,$$

where $n$ is the fluid refractive index.

The light beam produced by the SLD was collimated by using a collimation optic (Geltech Aspheric Lens with focal length = 4.51 mm, NA = 0.55 and, anti-reflection coating in the range 600-1050 nm — model C230TME-B, Thorlabs, USA).

The temperature of the TCM was controlled by using a thermoelectric temperature controller (TEC, model TED200C, Thorlabs, USA) and, the SLD was feed by using a diode controller operating in constant current mode (DE, model LDC200C, Thorlabs, USA).

The current photogenerated by the monitor photodiode was processed by the SCE to extract the interferometric signal. The SCE consists of a transimpedance amplifier and a high-pass filter described in our previous article. Finally, the output of the SCE was analyzed by using a dynamic signal analyzer (DSA, model SRS 785, Stanford Research System, USA).

$$L_c = \frac{0.44 \lambda_0^2}{n \Delta\lambda} \approx 11 \mu m,$$

2.3.2 Data Analysis Technique

An in-deep analysis of the Doppler spectrum provided by low-coherence SM systems is quite complicated and, a simplified analysis has been previously proposed.\(^8\)
Photons back-scattered by moving scatterers interfere on the PD active area both each other — homodyne — and, with photons due to the reference arm — heterodyne. Nevertheless, according to (6), a single particle moving along the streamline generates a single frequency tone in the Doppler spectrum with frequency $f_D$. Hence, the greater the number of scatterers moving with velocity $v_I$ and the greater the amplitude of the bin of the spectrum relative to the frequency $f_D$. As a result, a simplified analysis of the flow can be easily performed evaluating the frequency $f_{MAX}$ relative to the maximum amplitude in the Doppler spectrum.

2.4 Experimental Setup

Preliminary tests have been performed using a 0.4 mm internal-radius glass micro-cannula and two solutions of Intralipid (Kabivitrum Inc., Stockholm) and water as scattering media. As previously stated, in SM systems the shape of the Doppler spectrum depends on the scattering coefficient of the sample. Hence, to test the effects due to the variation of the scattering coefficient of the sample, measurements have been performed by using two solution of water and Intralipid having an Intralipid volume concentrations of 0.5% (solution $S_1$) and 1.5% (solution $S_2$), respectively.

As shown in Figure 3, the micro-cannula was fixed on a mechanical holder, then tilted and moved in order to be crossed by the light beam. Flow $Q$ was induced by using a syringe pump (Pilot Anestesia 2, Fresenius Vial, France) able to provide a nominal flow uncertainty lower than 1% ±0.05 ml/h.

![Figure 3. Picture of the experimental setup.](image)

3. RESULTS

In order to test the effects due to the variation of the scattering coefficient of the sample, measurements have been performed by using two solution (solutions $S_1$ and $S_2$). As an example, Figure 4 shows some Doppler spectra obtained by varying the flow $Q$ from 10 ml/h to 100 ml/h. Figure 5 shows the $f_{MAX}$ values — the frequencies relative to the maximum in the Doppler spectrum — obtained using the experimental setup described in subsection 2.4. Measurements
Figure 4. Doppler Spectra obtained by varying the flow $Q$ from 10 ml/h to 100 ml/h for solutions $S_1$ and $S_2$. For each of the investigated nominal flow $Q$, the figure shows 10 spectra each of which was obtained by averaging over 100 spectra acquired under repeatability conditions of measurement.
show in figures 4 and 5 have been obtained by using an impinging angle $\theta$ of about $88^\circ$.
The data show in Figure 5 have been obtained changing the nominal flow $Q$ from 10 ml/h to 1000 ml/h. Nevertheless, due to the limited bandwidth of the DSA (100 kHz), for solution S2 it has not been possible to investigate flows higher than 700 ml/h.

In order to reduce the noise contribute, for each of the investigated nominal flow $Q$, the $f_{MAX}$ value was obtained by averaging over 1000 spectra acquired under repeatability conditions of measurement (the overall acquisition time of the 1000 spectra was about 2 s).

The calibration curve shown in Figure 5 have been obtained by linear interpolation of the $f_{MAX}$ values as follows:

$$Q = m \cdot f_{MAX} + q.$$  

The obtained $m$ and $q$ values are reported in Table 1.

![Figure 5. Comparison of the $f_{MAX}$ values obtained changing the nominal flow $Q$ from 10 ml/h to 1000 ml/h for solutions S1 (◻) and S2 (○). The straight lines represent the calibration curves obtained by linear interpolation of the $f_{MAX}$ values. Due to the limited bandwidth of the DSA (100 kHz), for solution S2 it has not been possible to investigate flows higher than 700 ml/h.](image)

<table>
<thead>
<tr>
<th>Solution</th>
<th>$m$ (ml/h$^{-1}$Hz$^{-1}$)</th>
<th>$q$ (ml/h$^{-1}$)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.010</td>
<td>- 9.4</td>
<td>0.9969</td>
</tr>
<tr>
<td>S2</td>
<td>0.008</td>
<td>3.6</td>
<td>0.9991</td>
</tr>
</tbody>
</table>

4. DISCUSSION AND CONCLUSIONS

The developed measuring system is based on a low-coherence source exploiting the self-mixing (or internal) detection.
The proposed optical layout exploits the reflection from the internal wall of the duct, thus taking full advantage of the self-mixing detection. Indeed, classical optical layouts for low-coherence sources usually require a reference arm to set the VUT (sensing region or measuring region), limiting the potential advantages of the SM techniques. The proposed layout allows reducing system complexity, cost, size and increasing its robustness since the reference arm is the wall of the duct itself, thus movements of the measurand — the duct — basically does not affect the position of the VUT.

On the other hand, thanks to the usage of a low-coherence source, the measuring system greatly reduces the problems related to the poor definition of the VUT due to the fact that in SM systems the same optic acts as both illumination and collection optics. In fact, it is known that in LDV-SM the shape of the Doppler spectrum depends on the scattering coefficient of the sample, thus the measurement uncertainty suffers from variations in scatterers concentration e.g. due to variation in the blood hematocrit.

On the contrary, preliminary tests performed by using a micro-cannula and a solutions of Intralipid and water as scattering medium show that the measuring system is quite robust to variation of the scattering coefficient of the sample.

As an example, physiological blood hematocrit values range from 40.7% to 50.3% for males and, range from 36.1% to 44.3% for females, thus substantially ranging from about 36% to 50%. Since the scattering coefficient is a linear function of the scatterers concentration, the hematocrit values reported above imply that the variation of the scattering coefficient of blood due to the variation of the hematocrit is practically about ±15%. Conversely, the measuring system has been tested by varying the Intralipid concentration from 0.5% (S₁) to 1.5% (S₂) then varying the scattering coefficient of about 300%. Such a huge variation of the scattering coefficient leaded to a variation in sensitivity m of about ±20% (see Table 1).

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