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Optical feedback flowmetry: Impact of particle concentration on the signal processing method

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***Abstract*—Optical feedback interferometry (OFI) based flowmetry ~~allows for a~~ enables simple, robust, self-aligned and low cost ~~system~~ systems to measure the fluid flow velocity with reasonable accuracy. The particle concentration in the fluid causes significant changes in the signal of OFI sensors. While the spectral analysis of the particle induced Doppler shift remains as the most usual approach to determine the flow properties, different ~~signal processing methods have been recently~~ processing algorithms have been proposed in order to ~~accurately~~ evaluate the average ~~particle~~ flow velocity within the measurement volume. In this paper, the validity of the commonly used methods with regards to particle concentrations and flow rates is verified.**

***Index Terms*—Optical feedback, self-mixing interferometry, flowmetry, single scattering, multiple scattering, flow measurement.**

I. Introduction

ONE of the earliest applications of the laser after its advent was the measurement of velocity. The technique known as Laser Doppler Velocimetry (LDV) enabled the velocity measurement of fluid flow using an optical array that required to split a laser beam into two components and combine them in a measurement volume to create an interference pattern with bright and dark fringes [1]. A few years later, optical feedback interferometry (OFI) also called self-mixing interferometry was discovered by Rudd [2], which has the advantage of being compact, simple, self-aligned, and cost effective in comparison with traditional laser based measurements like LDV. OFI was then applied to measure physical parameters such as displacement, absolute distance, velocity, flow, and refractive index [3], [4]. Apart from industrial implementations, OFI is also used for biomedical applications [5], [6] including blood flow measurement [7], [8], blood perfusion measurement [9], and tissue phantom imaging [10].

In OFI based velocimetry (flowmetry), the signal spectrum is ~~analyzed to obtain the information regarding~~ calculated to determine the velocity of moving objects (particles) [11]. Since the ~~signal spectrum is~~ OFI spectra are generated from the Doppler shifted ~~feedback of particles embedded in the fluid, its morphology strongly depends on the velocity distribution of particles inside~~ light resulting from the interaction of the laser and the particles, their morphological features are strongly dependent on the distribution of velocities in the sensing volume. For the purpose of simplicity, the ~~”~~“sensing volume” is here considered as the volume where the particles are generating measurable contribution to the signal spectrum. Hence, the number of scattering ~~particles in the sensing~~ centers in the probe volume is also an influencing factor of the spectrum morphology. As the sensing volume is related to the optical configuration, ~~the impact of the optical system~~ it has a direct impact on the spectrum morphology that should also be considered [12].

Different signal processing approaches were proposed to extract the information regarding the particle velocities but, to the best of our knowledge, these methods were not evaluated as a function of the particle concentration, which becomes a relevant issue in multiple scattering media, which are mostly the media of interest in both chemical and biomedical applications. Moreover, a broad range of concentrations has been unexplored in previously published works.

In this paper, a simple OFI configuration using a single-lens optics is used as a reference laser flowmeter to evaluate the different signal processing methods. Particular attention is given to the impact of the particle concentration that demonstrates important results regarding the reliability of all different approaches.

In section II, the OFI based flow sensing principle is presented and the signal processing approaches for different signal spectrum morphologies are reviewed. In section III, the impact of the particle concentration is experimentally investigated and the domain of applications for the different signal processing is discussed.

II. Description of the fluid velocity evaluation methods

In OFI based flowmetry, light back reflected from the particles carried by the fluid is collected through the optical system and re-enters into the laser cavity causing a modulation of the laser emitted power at the Doppler frequency f_D. The Doppler frequency shift of the back-scattered electric field is related to the particle velocity V as [3]

$$f_D = \frac{2nV\cos\theta}{\lambda} \quad (1)$$

where λ ~~is~~ represents the laser wavelength, n is the refractive index of the ~~fluid~~liquid, and θ is the angle ~~between the laser~~

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~~beam propagation~~ formed by the laser propagaton axis and the particle velocity vector. An integrated photodiode inside the laser package is commonly used to monitor the laser intensity changes. To observe the Doppler frequency, a Fast Fourier Transform (FFT) is performed on the amplified photodiode current [8].

The back reflected light is the sum of contributions of each particle illuminated by the incident laser beam. Thereby, the velocity distribution of particles inside the sensing volume determines the frequency distribution in the signal power spectrum. As reported in the literature, when the sensing volume dimensions are small with comparison to the channel diameter, a well-defined Doppler peak appears in the power spectrum. However, in most practical situations with micro-scale channels, the Doppler frequency peak is very broad and may reach to an extent that no peak will be observed and the spectrum displays either a flat distribution [13] or a slow decay from low to higher frequencies [14].

In the case that flat frequency distribution occurs, a cutoff frequency approximation may be used to obtain the ~~Doppler frequency corresponding~~ maximum Doppler frequency related to the maximum fluid velocity [13], [15]. In this method, the frequency at which the ~~flat spectrum falls below a certain~~ plateau-like band in the spectrum is below a threshold (cutoff level) is considered as the Doppler frequency. This cut-off frequency is considered as the corresponding to the maximum flow velocity inside the measurement volume. In fact there is no robust criterion or algorithm to find accurately the cutoff frequency. It is shown in [16] that depending on the ~~particle concentration that~~ concentration of scatterers the cutoff level varies significantly. Moreover, the cutoff level is not only related to the concentration as the sensing volume dimensions may also have some influence. However, in case that the optics and the concentration of particles are fixed during the measurement as in most of the in vitro or ex vivo flowmetry cases, this method can be used to monitor the variations of the velocity [17].

In the case that the frequency distribution shows a decrease from low frequency to high frequencies without any noticeable plateau, the average particle velocity in the sensing volume can be obtained by calculating the weighted moment of the power spectrum which is given by [18]:

$$\overline{f} = \frac{M^1}{M^0} = \frac{\int_0^\infty f \cdot p(f)\mathrm{d}f}{\int_0^\infty p(f)\mathrm{d}f} \qquad (2)$$

where $\overline{f}$ is the average Doppler frequency ~~,~~ shift calculated from the ratio of moments M^1 ~~is the~~ and M^0. The first order moment ~~which~~ (M^1) is expected to be proportional to the average velocity ~~times the number of particles generating Doppler shifts in the sensing volume, M^0 is the~~ and to the amount of particles that contribute to the Doppler frequency shifts. The zero order moment ~~which is related to~~ (M^0) accounts for the number of particles ~~generating Doppler shiftsin the sensing volume, and~~ that produce Doppler shifts. $p(f)$ is the power ~~spectral density~~ spectrum of the OFI signal.

Reported works and experiment presented in this paper show that the flat distribution occurs when the particle density is low in the carrying fluid while continuous decay spectrum is likely to be observed at high density of particles cases. However to the best of our knowledge, this weighted moment method was never experimented in the case of low concentrations.

III. Results and Analysis

Various concentrations of particles are tested to evaluate the impact of the particle concentration in measuring the average Doppler frequency using the weighted moment of power spectrum and the cutoff frequency approximation method.

In order to obtain various concentrations of particles in the fluid flowing inside the channel, different dilutions of bovine full cream milk in demineralized water were used. Milk is an interesting fluid to be ~~used as it is a good~~ employed as an optical phantom for blood [19]. The milk concentrations by mass in water were: 2, 4, 6, 8, 10, 12.5, 25, 100% w/w.

A. Experimental setup

Fig.1 ~~details~~ depicts the experimental setup. The ~~laser diode~~ semiconductor diode laser (LD) was a Thorlabs L785P090 emitting at 785 nm a maximum power of 90 mW. ~~An~~ A focusing aspheric lens (Thorlabs C240-TME-B, ~~Thorlabs Inc.~~ focal distance f_d = 8 mm) was placed at twice its focal length from the laser source thus to obtain the sharpest focus and a good recollection of the feedback power by having the measurement volume at the closest possible distance to the lens. The laser beam was focused onto the cylindrical polydimethylsiloxane (PDMS) fluidic chip consisting in a unique circular channel with a diameter of 320 μm. A linear syringe pump (Picoplus, Harvard Apparatus) was ~~used to pump the fluid~~ employed to introduce the fluid flow into the channel at a controlled flow rate with 0.5% accuracy. The channel diameter being relatively large compared to the expected laser beam radius in the channel (10 to 20 μm), we have considered that any eventual lensing effect induced by the channel shape is neglectable in first approximation.

The output optical power is monitored by the photodiode (PD) integrated in the laser package. The signal of the photodiode is then amplified by a custom built trans-impedance amplifier (TIA). The laser, the lens and the electronic driver/receiver assembly were mounted on a xyz dc motorized stage (LSM050A, Zaber Technologies Inc.) controlled by a custom made Labview program. The assembly was tilted by 80.5 degrees with respect to the flow direction. The photodiode signal was acquired by a National Instruments data acquisition card (BNC-2110) with a sampling rate of 500 kHz. At each measurement ten consecutives frames of 8192 samples were acquired and the calculated spectrum was the average of the ten consecutive spectra.

B. OFI signal spectra

Each milk dilution has been pumped at ten different flow rates from 10 to 100 μl/min~~in steps of 10 l/min. At the maximum fluid flow rate (~~. At 100 μl/min~~)~~, the Reynolds number for the cylindrical channel was ~~about~~ calculated to be

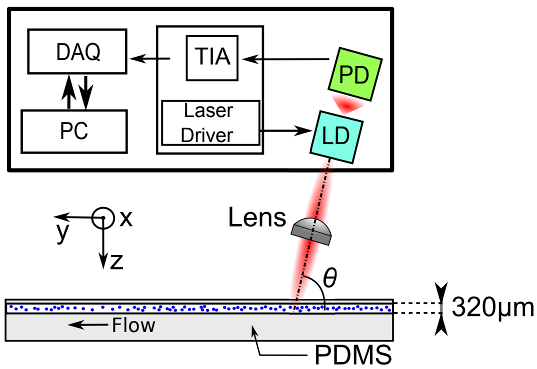

Fig. 1. ~~Schematic diagram~~ Fig. 1. Diagram of the experimental ~~setup~~system.

12, which is well within the laminar regime (Reynolds number < 2100). Figs 2 and 3 depict the signal spectra for all flow rates from 10 to 100 µl/min for milk concentrations of 2% and 100% respectively. As can be seen, due to the relatively large sensing volume with respect to the channel diameter, the OFI signal is a distribution of frequency shifts rather than a sharp Doppler peak.

The repetitive peaks at 40 kHz in the spectra are due to an electrical disturbing noise that is present even when the fluid is not in movement. These peaks do not impact the measurements by the cutoff frequency method, but they could be major with the weighted moment method. In order to make the weighted moment calculation less subject to the sensor noise, the spectral density of the OFI signal $p(f)$ in (2) is actually the difference between the sensor signal spectral density while liquid is flowing in the channel and a reference spectral density calculated in absence of flow (black curve in Figs. 2-4).

With the 2% concentration, the power spectrum is showing an almost flat distribution while at 100% milk concentration, a continuous decay is obtained and no flat distribution can be observed. As can be seen in Fig. 4, the evolution from flat plateau spectrum to continuous decay is progressive and at 25% the plateau is barely visible. Thus a natural limitation of the cutoff frequency method with regard to the particle density can be concluded.

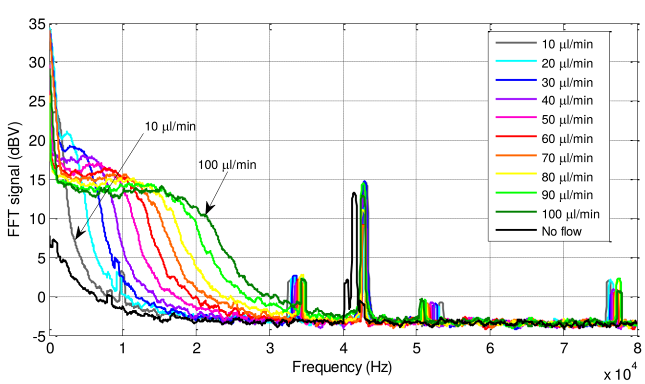

Fig. 2. Power spectra for flow rates from 10 to 100 µl/min with 2% milk concentration

The interpretation of these spectra is not trivial and if the signals obtained at low concentrations can be explained as the sum of Doppler shift contribution to the OFI signal from particles flowing at different positions from one wall to the other in the channel [20], the signals at higher concentrations show a more complex light-particles interaction such as attenuation, multiple scattering [8] , speckle [21], etc ...

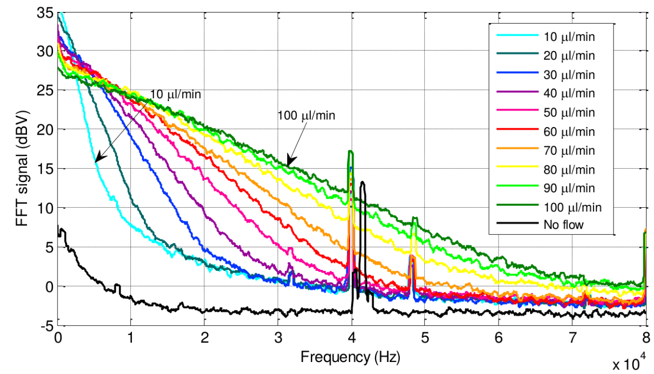

Fig. 3. Power spectra for flow rates from 10 to 100 µl/min with 100% milk concentration

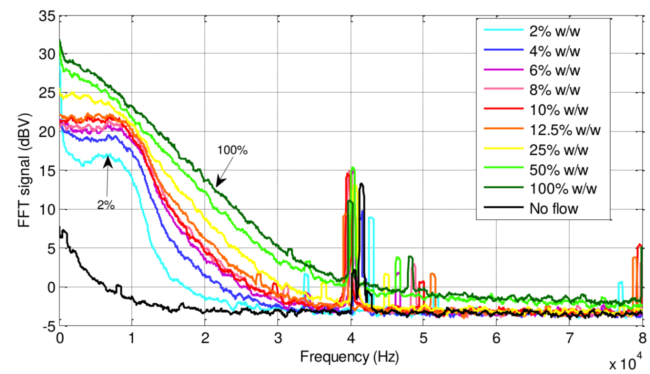

Fig. 4. Power spectra for varying concentration rates from 2 to 100% w/w with 50µl/min flow rate

However, the evolution of the OFI signal spectra with the concentration of scatterers shows the importance of the evaluation of the two main methods used to determine the local velocity of the flows against this parameter.

C. Evaluation of the methods against concentration

To evaluate the milk concentration range within which the cutoff frequency method and the weighted moment approximation are valid for the determination of the average velocity, the average Doppler frequencies have been calculated for flow rates from 10 µl/min to 100 µl/min. In a cylindrical duct, the maximum velocity is expected to be twice the average value calculated over the channel cross-section. In consequence, while the weighted moment method provides directly the average velocity value, we just divided by two the maximum Doppler shift that was obtained with the cutoff frequency method to obtain the average velocity value. Fig. ~~??~~ 5 shows the calculated average Doppler frequency shift obtained with the cutoff method and the weighted moment method for 2, 4, 10, 25% w/w concentrations while Fig. ~~??~~ 6 shows the average Doppler frequency shift with the weighted moment

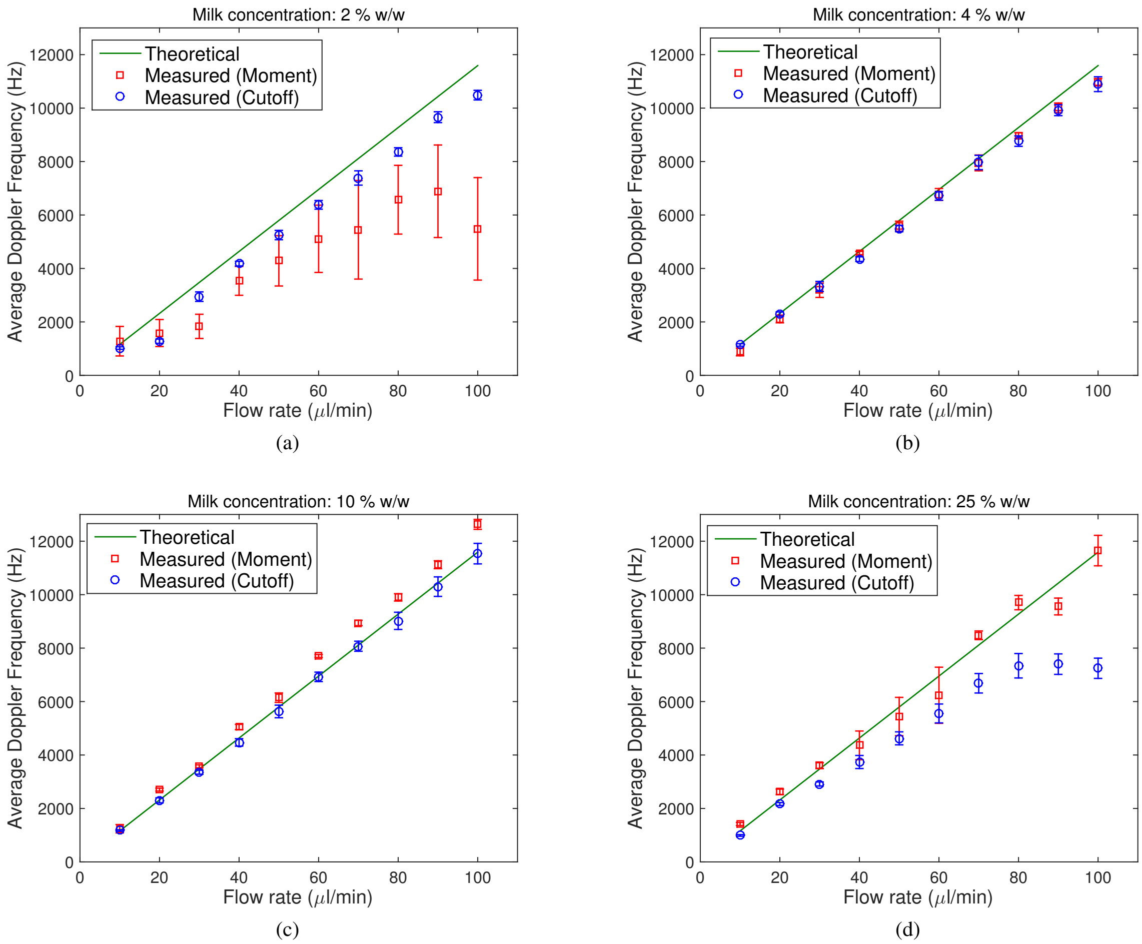

Fig. 5. Average Doppler frequency ~~(~~calculated with the cutoff frequency method (blue circles) and the weighted moment method (red squares) versus flow rates for milk concentrations of 2, 4, 10, 25% w/w. ~~The green circles shows the average Doppler frequency as calculated with equation .~~ Error bars are standard deviations calculated from 10 measurements.

method for ~~2, 4, 10,~~ 100% w/w concentrations. In ~~both~~ these figures, the error bars show the standard deviation calculated from 10 consecutive measurements.

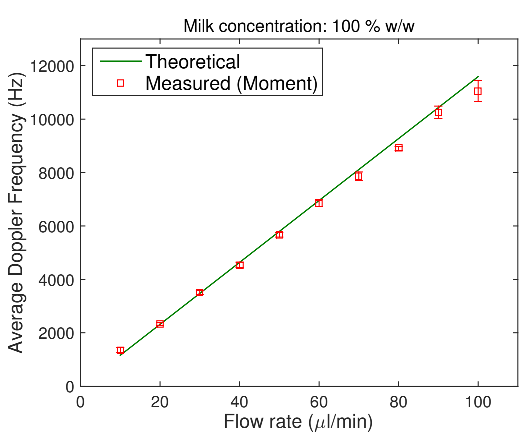

Fig. 6. Average Doppler frequency ~~(~~obtained by the weighted moment approximation ~~)~~ versus flow rates for milk concentrations of ~~2, 4, 10,~~ 100% w/w. The red circles shows the average Doppler frequency as calculated with equation (1). Error bars are standard deviations calculated from 10 measurements.

As can be observed, both methods show a good linear trend of the average Doppler frequency with the flow rate in the channel. However, for the 25% w/w concentration, the cutoff frequency method shows a strong deviation from this linear trend. This is due to the difficulty of detection of the actual cutoff frequency of the spectrum at such concentrations. At higher concentrations, the cutoff frequency method is not anymore relevant. For the weighted moment method, the average Doppler frequency measurement for 2% milk concentration is not reliable, not only because of the significant deviations from the expected linear relationship but also because of low repeatability of the measurement over the 10 measurement. From 4% to 100% concentrations, the calculated average frequencies show very small deviations from the expected values as can be seen in Fig. 6.

Fig. 7 shows the relative error for both ~~the cutoff frequency method and the weighted moment method~~tested processing methods. Fig. 7a presents the evolution of the relative error (averaged over the flow-rate range) with the milk concentrations, while Fig. 7b presents the evolution of the relative error (averaged over the concentration range) with the flow rate. In the calculated values of figure 7b only the concentration where the method is efficient have been taken into account which means that for the cutoff frequency method milk concentrations higher than 25% have been discarded while for the weighted moment, method milk concentrations lower than 4% have been discarded.

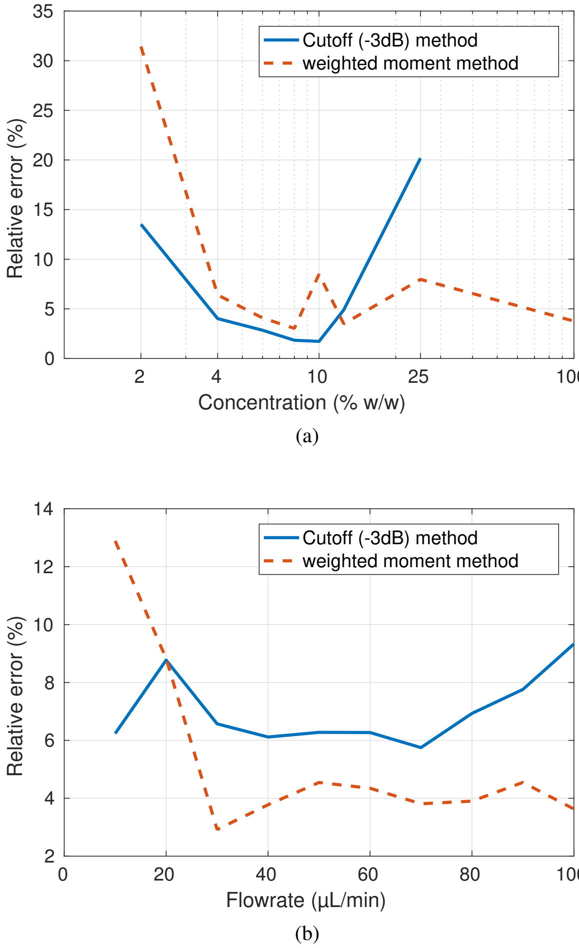

Fig. 7. Relative error of the cutoff frequency method (blue solid line) and the weighted moment approximation (red dashed lined) with regard to the value expected from equation (1). (a) Against milk concentration ratios by averaging the values obtained at each flow rate and (b) against flow rate by averaging the value obtained for each milk concentration except for concentration ratio lower than 4% for the weighted moment method and above 25% for the cutoff frequency method.

Fig. 8 shows, with a similar approach, the evolution of the relative standard deviation against concentration (Fig. 8a) and flow rate (Fig. 8b). In Fig. 8b the measured relative standard deviation calculated at very low concentration ratio (under 4% w/w) have not been taken into account for the calculation of the average values by the weighted moment method.

Fig.7 and 8 show, as expected, that the concentration of scatterers has a much bigger impact on the ability of the two methods to measure the local velocity than the flow rate has. Also, the cutoff frequency method appears as a more robust method with a stable relative error and a much lower relative standard deviation for any flow rate and for any milk concentration as long as the plateau remains visible in the signal spectrum.

The robustness of the weighted moment method is degraded for both the highest dilution (2% concentrated milk in mass) and, to a lesser extent, for the lowest flow rate. We believe this may be due to the low values of both the zero and

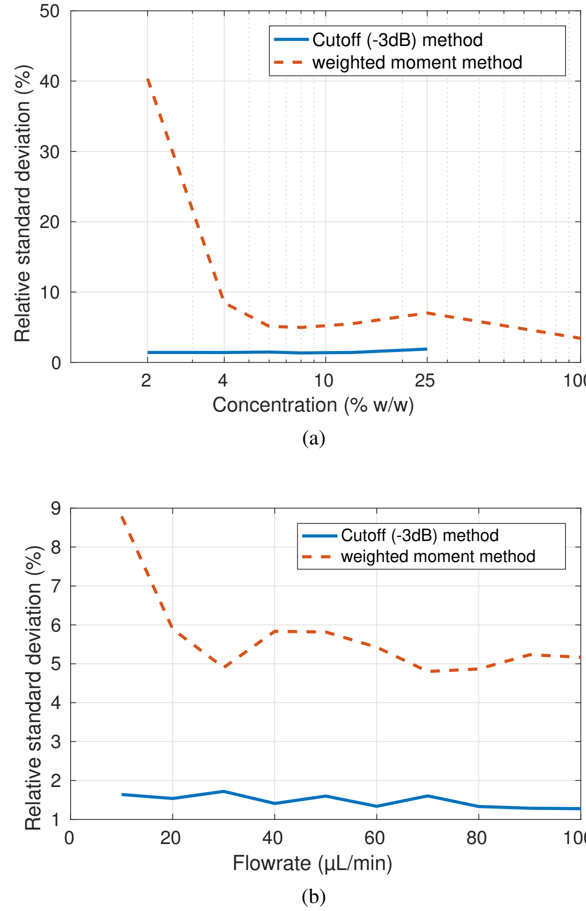

Fig. 8. Relative standard deviation for the cutoff frequency method (blue solid line) and the weighted moment approximation (red dashed lined) with regard to the value expected from equation(1). (a) Against milk concentration ratios by averaging the values obtained at each flow rate and (b) against flow rate by averaging the value obtained for each milk concentration except for concentration ratio lower than 4% for the weighted moment method and above 25% for the cutoff frequency method.

the first order moments which induce a higher sensitivity of these quantities to any energy of the signal spectrum that is not related to the Doppler effect: the electrical noise (mostly Flicker noise), the mechanical noise (any residual variation of the laser-fluidic chip distance) or the Speckle effect that can occur on the microfluidic chip surfaces. While the weighted moment relative standard deviation at low flow rate remains in an acceptable range, the degradation at low concentrations is dramatically high and this method should be discarded to the benefit of the cutoff frequency approximation method.

IV. Conclusion

In this work, Optical Feedback Interferometry based flowmetry using a single lens has been presented to measure the fluid velocity at various particle concentrations and different flow rates. We have used diluted milk from 2% concentration in weight to 100% (no dilution) causing signal spectrum distribution change from a flat distribution of power at low concentration rate up to a slow decay with frequency at the highest concentrations. We have shown that the weighted moment approximation cannot be used to accurately estimate the average Doppler frequency in the case of highly diluted milk solutions, while for moderate milk concentrations up to full milk it is a robust and reliable method with relative standard deviations below 10%. The cutoff frequency method is a much more efficient method at very low concentration and a slightly more robust and reliable one at moderate concentrations, but it is not suitable for higher concentrations of scatterers as the signal spectrum power distribution does not allow for the determination of a significant cutoff frequency. All experiments have been performed using milk and demineralized water and the results presented can be extended to any solution with similar scatterer sizes and densities as in particular blood flows.

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