 Fundamental study for measuring microflow with Michelson interferometer enhanced by external random signal

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Abstract
We propose a measuring technique for microflow based on the stochastic resonance phenomenon. The minute changed signal from the microflow hidden within the threshold of multi-threshold imaging sensors, such as CCDs, can be reconstructed using an external random signal. The differences in optical path length fringes of a Michelson interferometer were enhanced by scattered light using a micro Brownian particle solution. In this paper, we investigate the required characteristics of the external random signal numerically and experimentally. The feasibility of the proposed method was experimentally confirmed. The number of pixels required to reconstruct the signal was smaller than expected owing to internal and environmental noise signals. We show that the standard deviation of the external random signal plays an important role in enhancing the accuracy of the measurement.

Key words: Microflow, Stochastic resonance, Interferometer, Optical path difference, μ-TAS, CCD

1. Introduction

Recently, there has been significant growth of research into microdevices that use the flow of liquid reagent in micro channels, such as lab-on-chip and micro-total analysis system (μ-TAS) devices. It is not straightforward to evaluate reactions, mixing or separation of fluids because of the scale effect and hence to understand the microflow in these devices (Arora et al., 2010). A measurement technique for microflow is necessary in order to clarify characteristics such as velocity, density, temperature and composition. Micro particle image velocimetry (micro-PIV) has been developed as the measurement technique for velocity distributions of microflows (Sinton et al., 2004). However, the refractive index of the microflow is difficult to measure, although it is effective for analyzing microflow properties. Understanding the refractive index in microflow helps in monitoring the material composition, mixing, chemical reaction process and so on. This study employs a light interferometer to sense the minute change of optical path length from the microflow refractive index. For the visualization of a flow-field, a two-dimensional image sensor, such as a charge-coupled device (CCD) camera, is necessary. However, the dynamic range of these image sensors is narrow. The quantization process degrades the resolution, and unwanted internal noise, such as shot or readout noise is caused. To address these problems, this study aims to establish a method for measuring refractive index with high sensitivity for the visualization of microflow using external random signals.

There are several methods to compensate the quantized data in an image, such as dithering (Gammanitoni, 1995) and digital or low pass filters. These techniques treat the already-quantized data and hence interpolate the images. It is not possible to restore the original signal, because the information between discrete signals has already been lost. The proposed method aims to reconstruct the original signal hidden in the sensor threshold. In many biological systems, the detection of a weak signal has been achieved using external or internal signals. This is explained by a phenomenon called stochastic resonance (Gammanitoni, 1998), in which the signals hidden within the sensor threshold can be obtained by adding an appropriate additional external signal. In order to realize this method, the properties of the external signal are essential, being required same physical quantity as the original signal. This study proposes to use the scattering random signal as the external signal to stimulate the image of the interference fringes. A CCD camera is used
as a sensor. Our purpose is to verify the feasibility of this visualization method for microflow based on stochastic resonance. This method would be best suited for the case in which the optical path difference from the microflow does not generate a steep change temporally or spatially.

2. Principle

In analogue to digital conversion, minute changes in the signal are hidden in the threshold of the sensor, such as CCD. We propose a measurement principle for the interferometer that will reconstruct the hidden information within multi-threshold sensors on the basis of stochastic resonance (Michihata et al., 2013; Tran et al., 2013). The fundamental concept of the multi-sensor detecting system based on stochastic resonance (Collins et al., 1995) is shown in Fig. 1(a). One original signal is considered (Fig. 1(b)). An external random signal (Fig. 1(c)) is added to the original signal before it reaches the sensors in order to stimulate the sensor (Fig. 1(d)). The external signal must be independently random for each sensor. The sensor digitizes the original signal together with the external random signal (Fig. 1(e)). These discrete signals are then summed and averaged to reconstruct the original signal (Fig. 1(f)). To apply this concept, multiple sensors are required, and these should be multi-threshold sensors.

In practice, the original signal consists of interference fringes varying in space and time according to the microflow. To measure the microflow, a CCD camera is employed as the multiple threshold sensor array. Therefore, the original signal is not identical to the measured signal. Although different signals are incident on different sensors, several neighboring sensors are used to average the signal so that differences between the measured signal and incident signal to each sensor are minimized. This directly relates to the measurement accuracy. The larger the number of sensors averaged, the more precise the measurement. The sensors are averaged spatially and temporally as shown in Fig. 2. The output of sensors, \( P_{(i,j)} \), are averaged along with the sensor number, \( i \), and time, \( t \), (or frame number) to obtain the

![Diagram](image_url)

Fig. 1 Concept of signal detection based on the stochastic resonance
averaged output intensity $P_{\text{ave}}$ as follows, where $a$ and $b$ are the first and last sensor number, respectively.

$$P_{\text{ave}} = \sum_{i=a}^{b} \sum_{j=0}^{n} P_{i,j},$$

(1)

3. Simulation

3.1 Simulation model

First, we investigate the properties of the proposed method using a computer simulation prior to experiments. Our proposed system incorporates a Michelson interferometer, which is illustrated in Figure 3, with the measured parameter being the change of the optical path length. A CCD camera was used as multiple threshold sensors to measure the intensity of the interference fringes. The light beam propagates through the sample. We assume that the refractive index of the sample changes slightly and uniformly. This variation produces a change in the optical path length, resulting in changes of the intensity distribution of the interference fringes in the CCD. For simplicity, it is presumed that all pixels of CCD camera receive the exact same change in one frame. These variations of the refractive index are set equivalent to an intensity of the interference fringes smaller than 1 gray level of the CCD. The interfered light is combined with the external random signal, which has a spatially and temporally random intensity distribution. The mixed beam is incident to the CCD. The intensity of the mixed beam is

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \left(4\pi d \Delta n / \lambda + \phi \right) + \delta_i,$$

(2)

where $I$, $I_1$, and $I_2$ are the intensity of mixed beam at CCD, object beam and reference beam, respectively; $\phi$ is the phase difference in the object and reference beams; $\lambda$ is the wavelength of the light source; $d$ is the thickness of the sample; $\Delta n$ is the change of the refractive index of the sample; $\delta_i$ is the intensity of the external random signal; and $i$ is the pixel number of the CCD. The CCD used was 8 bits, so the intensity of the interference fringes was quantized by 256 gradations. The wavelength of the light source was 633 nm. In the simulation, the external random signal was treated as a signal with white Gaussian distribution (zero mean). The standard deviation of the external random signal was varied from 0 to 0.01. The number of the sensors is determined by $N$ pixels in the CCD. The correlation coefficient, $C$, was used to quantify the effect of the external random signal,

$$C = \frac{\sum_{i=1}^{m} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{m} (x_i - \bar{x})^2 \cdot \sum_{i=1}^{m} (y_i - \bar{y})^2}}, \quad \bar{x} = \frac{\sum_{i=1}^{m} x_i}{m}, \quad \bar{y} = \frac{\sum_{i=1}^{m} y_i}{m},$$

(3)

where $x_i$ and $y_i$ are input and output data, and $m$ is the number of data points. A preliminary calculation shows that a change of 1 grayscale level in the CCD is equivalent to a change of 0.0156 in the intensity of the interference fringes, $I$, and also equivalent to a change of $3.15 \times 10^{-3}$ in the refractive index of the sample, $\Delta n$. 

3.2 Simulated result

The possibility of reconstructing the original signal using the external random signal was checked. The conditions of the simulation were: \(I_1 = I_2 = 1\), \(d = 100 \text{ µm}\), and \(\varphi = 6.09\ \text{rad}\). Standard deviation of \(\delta_i = 0.0049\). The maximum variation width of \(\Delta n = 1 \times 10^{-6}\), which results in changes in the intensity of the interference fringes smaller than the threshold of the CCD sensors. The number of the sensors, \(N\), was 400. The simulated results are shown in Figure 4. As shown, the input signal, smaller than the threshold of the CCDs, could be reconstructed. The correlation coefficient of this reconstructed signal was 0.94. The proposed method was compared with normal detection by the CCD for the case of a ramp function as the input signal. The thickness of the sample, \(d = 50 \text{ µm}\); the intensity of the external random signal at that pixel, \(\delta_i = 0.006\); and the maximum variation width of refractive index, \(\Delta n = 0 \text{ to } 1 \times 10^{-4}\). Figure 5 shows the simulated result. Without the external signal, the smoothly changing signal was not measured correctly. However, the output signal of the proposed method follows the input signal, which verifies the effectiveness of the proposed method.

We then examined the influence of the amplitude of the external random signal, which is controlled by the standard deviation. The standard deviation of the external random signal was varied from 0 to 0.01 with different numbers of sensors, \(N\). Other parameters were fixed: \(d = 100 \text{ µm}\), \(\varphi = 6.09\ \text{rad}\), and \(\Delta n = 1 \times 10^{-6}\). As shown in Fig. 6, the external random signal produces the maximum of the correlation coefficient. Considering that a standard deviation of 0.0156 is equivalent to 1 gray level, the standard deviation of the external random signal must be smaller than half of 1 gray level of the CCD. With a large number of sensors, the correlation coefficient was close to 1 and steeply increased with the standard deviation of the external random signal. This clearly shows that the number of sensors is highly important to improve the sensing performance. We also note that the correlation coefficient decreased for increased standard deviation of the external random signal. This means that increasing the amplitude of the external random signal above the ideal level no longer enhances the sensor performance. This relationship of the standard deviation with the correlation coefficient depends on the original signal. When the original signal varied greatly, the optimal standard deviation became close to half of 1 gray level. Therefore, the amplitude of the external random signal must be tuned depending on the conditions such as the number sensors in the CCD.

The resolution was evaluated as follows. A step signal of a certain height was input together with the external random signal. The output signal was evaluated if it can be distinguished into two regions before and after the additional step signal, as shown in Fig. 7, Step 1 and Step 2, respectively. The parameter, \(D\), is introduced to evaluate the resolution

\[
D = \left( T_{\text{step}2} - \sigma_{\text{step}2} \right) - \left( T_{\text{step}1} - \sigma_{\text{step}1} \right),
\]

where \(I\) bar and \(\sigma\) are the average and standard deviation of the mixed intensity output signal, respectively. When the value \(D\) is positive, the signal is considered to be distinguished. The minimum change of the refractive index at the smallest value \(D\) is considered as the resolution of the system. In this case, \(d = 100 \text{ µm}\), and the standard deviation of the external random signal was optimized from 0 to 0.03 every time. The simulated result is shown in Fig. 8. By increasing the number of sensors the resolution was rapidly improved. Considering both Fig. 6 and Fig. 8, the number

![Simulated reconstruction of the CCD signal.](image1)

![Simulated reconstruction of the ramp signal](image2)
of sensors should be larger than 100 to obtain better sensing performance. On the other hand, a small number of the sensors is required, as mentioned above. This implies that there is an optimum number of sensors.

The performance of the proposed method is deeply influenced by the phase difference between the signal and sensor thresholds (Fig. 9). Among sub-threshold signals, a signal near the threshold (Signal 1) can be stimulated with an external random signal of small amplitude. A higher amplitude external random signal is needed to stimulate the signal in the center of the upper and lower threshold region (Signal 2). Thus, the phase difference should be discussed. For this investigation, the input signal was set to be a sinusoidal wave. The response amplitude was compared with the noise amplitude of different frequencies (signal to noise ratio, SNR). Changing the phase difference, \( \phi \) from 7.1 to 7.75 mrad, the maximum amplitude ratio was as shown in Fig. 10. As anticipated, higher SNR was obtained for the signal near the threshold and the lowest for signals near the center of the threshold region. This nonlinear performance should be noted as an important property of the proposed method.

4. Experiment

4.1 Experimental setup

A schematic of the experiment setup for testing the feasibility of the proposed concept is shown in Fig. 11. It is a

Fig. 11  Experimental setup

Fig. 12  Size distribution of particles

Fig. 13  CCD image of the scattered light. The image brightness has been increased to aid the reader

Table 1  Standard deviation of the scattered light

<table>
<thead>
<tr>
<th>Laser power [µW]</th>
<th>Standard deviation [gray level at 8-bit]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spatial</td>
</tr>
<tr>
<td>62</td>
<td>1.4</td>
</tr>
<tr>
<td>118</td>
<td>2.6</td>
</tr>
<tr>
<td>237</td>
<td>5.1</td>
</tr>
<tr>
<td>341</td>
<td>8.6</td>
</tr>
<tr>
<td>816</td>
<td>19.2</td>
</tr>
</tbody>
</table>

Michelson interferometer based system, which consists of the Michelson interferometer as the original signal and the scattered light as the external random signal. The light was mixed at beam splitter 2. Two different lasers are used as a light source to avoid the interference between the original signal and the external signal. The laser diode ($\lambda = 532$ nm) for the interference fringes and the He-Ne laser ($\lambda = 632.8$ nm) for the scattered light are employed. The laser power was adjustable using the variable neutral density filters (filter 1 and filter 2 in Fig. 11). Fine positioning of mirror 1 was controlled by a piezo-stage. A CCD camera (8-bits, 30,000 pixels) was used as the multi threshold sensors. The pixel size of the CCD is 6 µm × 6 µm. To reduce the environmental effect (temperature fluctuation and air turbulence), the whole the optical system was accommodated in a heat-isolated box. To test the proposed principle, instead of a microflow sample, mirror 1 was tilted to provide the change of the optical path length, causing the interference fringes on the CCD.

Scattered light was used as the external random signal, derived from a micro Brownian particles solution prepared by silica particles and alcohol solvent. For the stochastic resonance, the external signal must be random for time and for
each single pixel (Collins et al., 1995). Dynamic light scattering has been previously confirmed to provide an appropriate scattering length (Tran et al., 2013). The average size of the silica particles was 400 nm (see Fig. 12). The concentration of the particles in the solution was 8.0 g/L.

4.2 Randomness of external signal

Figure 13 shows the image of the scattered light taken by the CCD, which shows the external signal is spatially randomly distributed over whole sensor array of the CCD. The images were taken for 100 frames with the frame rate of 5 fps. The laser power was varied from 62 µW to 816 µW. The pixels were evaluated to calculate the standard deviation of the intensity for 400 pixels (20 pixels × 20 pixels) for each image. The temporal property was evaluated by calculating the standard deviation of the intensity of a randomly chosen fixed pixel across each of the 100 frames. The results are shown in Table 1. The standard deviation changes with the laser power as expected. Thus, the standard deviation of the external random signal can be tuned by the laser power. However, if the laser power of the scattered light were high, the intensity of the mixed light (original signal and external signal) incident onto the CCD is dominated by the external random signal. Therefore, the laser power should be set as small as possible not to influence the original signal.

4.3 Measurement of interference fringe with the external random signal

4.3.1 Feasibility of the proposed method

Feasibility of the proposed method was experimentally confirmed. An 8-bit CCD was used as reference to check the performance of the signal reconstruction. The 8-bit-signal was converted into a 4-bit-signal and this 4-bit-signal was applied as the pseudo-original signal to test the performance of the proposed method. The 16 gray levels at 8-bits was shrunk to 1 gray level at 4-bit. Mirror 1 was slightly tilted to induce interference fringes on the CCD as shown in Fig. 14. The optical path length of the measured sample was not varied temporally in this case. The image was taken for 100 frames in series at a frame rate of 5 fps. The standard deviation of the external random signal was set to 6 gray levels at 8-bits, which is 0.38 gray levels at 4 bit, and the laser power was set to 250 µW.

The intensity of interference fringes with the external random signal was compared to the intensity without the external random signal. Figures 15 and 16 show that results of one intensity profile of the interference fringes (A to B in Fig. 14) without and with the external random signal, respectively. In this case a single pixel was averaged over the 100 frames. Black and red plots indicate the 8-bit and 4-bit data, respectively. Figure 15(a) shows the averaging method itself has a significant effect to interpolate the profile, however, there are still quantized signals found in Fig. 15(b). On the contrary, Fig. 16 shows that the external random signal could enhance to obtain the hidden data. It was possible to reconstruct a smaller change than the 1 gray level at 4-bit (see Fig. 16(b)). We note that the intensity profile of 4-bit is lower than one of 8-bit as seen in both Fig. 15 and Fig. 16. This is because the conversion process (8-bit into 4-bit) produces a half-bit bias in the intensity profiles.

These results clearly show the effect of the external random signal to reconstruct the hidden data.

4.3.2 Pixel averaging effect

As mentioned above, the number of pixels at one frame to average should be as small as possible when considering

![Fig. 14 Representative image of interference fringe with the external random signal](image)
Fig. 15 Intensity profile (A to B) of the interference fringe without the external random signal

Fig. 16 Intensity profile (A to B) of the interference fringe with the external random signal

Table 2 Conditions for averaging pixels

<table>
<thead>
<tr>
<th></th>
<th>Spatial pixel</th>
<th>Temporal pixel</th>
<th>Total number of pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1 (1×1)</td>
<td>100 frames</td>
<td>100</td>
</tr>
<tr>
<td>Case 2</td>
<td>4 (2×2)</td>
<td>25 frames</td>
<td>100</td>
</tr>
<tr>
<td>Case 3</td>
<td>9 (3×3)</td>
<td>11 frames</td>
<td>99</td>
</tr>
</tbody>
</table>

Fig. 17 Interference fringes with three different averaging
the accuracy of reconstruction. The results shown in Figs. 15 and 16 were temporally averaged, which decreases the temporal resolution. Therefore, the intensities of the pixels are averaged both spatially and temporally, as shown in Fig. 2. The number of pixels is fixed to 100. Three different averaging methods are compared as summarized in Table 2, and the resultant intensity profiles are shown in Fig. 17. There is no remarkable difference because the number of pixels used was almost the same in each case. However, we note that case 3 (red line in Fig. 17) exhibits a flatter profile. This is because spatial averaging by 3×3 pixels is the effect of a low pass filter. However, the temporal resolution is 10 times greater owing to the low frame numbers required. Therefore, if we sacrifice spatial resolution, the number of pixels to average in the spatial domain for any one frame should be increased.

4.3.3 Influence of the number of frame to average

Our simulation study found that the number of frames to average is important to the performance of the proposed method, as shown in Figs. 6 and 8. To increase the accuracy of the measurement, the number of the frames should be increased. However, the higher number of frames makes the measurement resolution worse. We investigate the influence of the number of the frame experimentally. At fixed spatial averaging (set to 1×1); the temporal averaging was varied by averaging over different numbers of frames. Figure 18(a) shows the results for the whole profile and Fig. 18 (b) and (c) show the detailed parts. Surprisingly, even averaging 5 frames works as shown in Fig. 18(b) where the intensity distribution by averaging 5 frames is well agreed with others (50 frames and 100 frames). However, if carefully looking at Fig. 18(c), the averaging 5 frames has errors and the signal is still quantized. Averaging over 50 and 100 frames shows only a very slight difference from each other. Therefore, the optimum number of frames to average lies between 5 to 50 frames.

![Fig. 18 Interference fringe with different temporal averaging](image1)

![Fig. 19 Experimental result to compare averaging effect in temporal and spatial domain](image2)
The reason why averaging 5 frames still works is considered to be the existence of internal and environmental noise signal. In the measurement system, there is always the shot and read out noise in the CCD, which was about 2 gray levels at 8-bit in our setup. Environmental fluctuations such as vibration, temperature fluctuation, air turbulence are further noise sources. All environmental and internal noise induces about 10 gray levels peak to peak. These signals may serve as the random signal, so the total external random signal can be larger than expected. These environmental and internal noise signals are also the reason why simple averaging is able to interpolate the profile, as shown in Fig. 15.

4.3.4 Influence of the standard deviation of the external signal

As shown in Fig. 6, the standard deviation of the external random signal is important to enhance the measurement accuracy. Also as expected, at the same standard deviation, the measurement resolution is different in terms of the phase lag to the sensor threshold. It is not easy to change only the standard deviation experimentally (the intensity of the scattered light is also changed). Therefore in this case, the standard deviation of the external random signal was fixed and the threshold was changed. That is, 8-bit signal was converted into 3-bit and 4-bit signals for comparison. The measurement conditions were the same as the previous investigation above. The standard deviation of the external random signal was set to 6 gray levels at 8-bits, which is 0.38 gray levels at 4 bit and 0.19 gray levels at 3 bit. Spatial and temporal averaging were 1×1 and 100 frames, respectively. The result is shown in Fig. 19. The intensity profile of the 3-bit is still quantized at many parts. This is because the standard deviation of the external random signal is too small to stimulate the original signal. This implies that accuracy depends on the standard deviation of the external random signal. Therefore this has to be optimized against the height of the threshold of the sensor used.

5. Conclusion

We proposed a measuring technique for microflow by employing a Michelson interferometer enhanced by an external random signal. The minute changed signal hidden in threshold of the multi-threshold sensor can be reconstructed by adding the external random signal to the original signal. Our findings are summarized as follows.

1) We experimentally proved that the external random signal could enhance the performance of the measurement.
2) The number of pixels to average is smaller than expected in the simulation study because internal and environmental noise is incorporated into the external random signals. Therefore, the reconstruction of the signal could be achieved with less than 50 pixels.
3) The standard deviation of the external random signal plays an important role in improving the accuracy of the measurement. Hence, it is important to optimize the relation between the standard deviation of the external random signal and the height of the threshold of the sensor.

As a multi-threshold sensor, 8-bit CCD was used in this paper. This method is expected to be applicable other sensors with appropriate external random signal.

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