Single Channel Instrument for Simultaneous Rotation Speed and Vibration Measurement Based on Self-Mixing Speckle Interference

Xiulin Wang, Huiru Yang, Lu Hu, Zhen Li, Hanqiao Chen, and Wencai Huang

***Abstract*—In this paper, a novel method for simultaneous measurement of rotation speed and vibration based on self-mixing speckle interference (SMSI) has been demonstrated. In view of the autocorrelation characteristic of SMSI, the time delay of laser incident during one rotation period is determined, and the rotation speed of the object is calculated according to the mathematical relationship. At the same time, the signal square-wave conversion and the global maximum fringe-counting method are proposed to measure the vibration displacement subject to the rotation. The theory and signal processing means are introduced in detail, and a series of experiments employing computer disk at different positions with various rotation speeds indicate that the proposed method achieves a simple, efficient, and accurate multi-parameter measurement.**

***Index Terms*—Self-mixing interference (SMI), rotation speed measurement, vibration measurement.**

I. Introduction

It IS well-known that non-contact measurement of key parameters such as speed and vibration displacement are increasingly essential in microelectronics industry, quality control, and nondestructive testing applications. Self-mixing interference (SMI) is a phenomenon in which part of the emitted light is reflected or scattered by the external object and re-enters the laser cavity, resulting in fluctuations in the power and frequency of the laser. Owing to its advantages of compactness, intrinsic simplicity, and self-alignment, SMI has become a new kind of sensing technology and is extensively used in measuring displacement [1]–[3], velocity [4], [5], distance [6], [7], vibrations [8]–[10], 3D imaging, biomedical sensing [11] and other occasions [12]. In 1999, K.Özdemir firstly proposed a method for measuring velocity and length of moving surfaces simultaneously by a speckle velocimeter [13]. Up to date, several schemes of applying SMI to realize the simultaneous measurement of multi-parameter has been achieved [14]–[17], but so far there is no relevant report on the simultaneous measurement of rotation speed and vibration. However, simultaneous measurement of vibration information for rotating objects is beneficial to monitoring the safety and stability of rotating objects. The SMI vibration measurement methods are roughly divided into the two categories: fringe counting method and phase-unwrapping method, in which phase-unwrapping method requires complex calculation to estimate the values of the optical feedback factor and linewidth enhancement factor. Due to a single fringe in the SMI signal corresponds to a half-wavelength displacement of target, it is easy to reconstruct the vibration information of the target by using the fringe counting method [18].

The laser self-mixing interferometric velocimeter has been developed very maturely, among which the Doppler velocimetry [4], [19] and speckle velocimetry [20], [21] has been widely employed. Since the magnitude of the Doppler frequency shift is proportional to the velocity and the cosine of the incident angle, the control of the incident angle will introduce some measurement errors in the experiment. In 2012, Tanios [22] *et al.* proposed a double-head LD velocity sensor, which effectively reduced the sensitivity of the system to angle variations. Nevertheless, the velocity increase will correspondingly lead to higher requirement on the sampling frequency of the experimental equipment via Doppler velocity measurement method, which limits its application to some extent. Another velocity measurement method by using self-mixing speckle interference (SMSI) overcame the above limitations and has attracted considerable research attention [23]. Whereas, when using SMSI to measure the velocity of an object, it is usually necessary to extract relevant features through signal processing, and perform a linear fit to the relationship between the speed and these parameters. In 2018, Gao [24] *et al.* proposed a rotation speed measurement method using a cross-correlation algorithm to analyze the dual-beam self-mixing speckle signal. This method does not need curve fitting to reckon the speed, and can achieve high-speed measurement at a low sampling rate with a relative error of less than 4%. In the same year, they [25] developed a rotation speed measurement method based on the autocorrelation function, which only needs to perform autocorrelation calculations on a single-channel SMSI signal to obtain the object's rotation speed through time delay.

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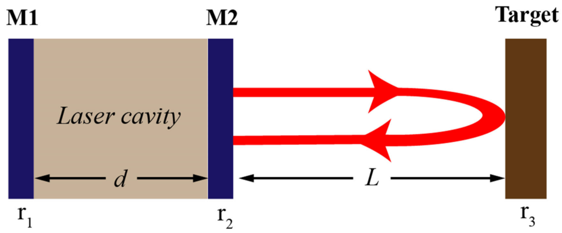

Fig. 1. Three-facet Fabry-Perot model.

In this paper, we propose a novel method based on SMSI to measure the rotation speed and vibration of an object simultaneously. When the laser beam is perpendicular to the rotational tangent speed of the object, autocorrelation processing is conducted to obtain the signal period, and then the rotation speed can be calculated. The vibration information of the object is determined by using the global maximum fringe-counting method after performing square-wave transformation on the signal. In the experiment, we carried out simultaneous measurement of rotation speed and vibration for a computer disk, and finally verified the feasibility of the method through the regular pattern of vibration amplitude with rotation speed. The proposed method contributes to the non-contact testing of equipment and the quality control of products in industry, therefore shows great application potential.

II. Theoretical Analysis

The self-mixing speckle signal caused by the scattering of external objects is modulated by amplitude and phase, and the reflected light also carries the movement information of the object. If the position change of the light spot will cause the surface roughness of the moving object to change, the spatial distribution of the speckle field will also change. At this time, it is called dynamic speckle, which can realize speed measurement.

Two beams of light produce interference, and according to the Huygens-Fresnel principle, the superimposed interference between the secondary wave expression of the output power change due to the SMI forms diffraction fringes. The scattered field can be expressed as [26]:

$$E\left(x,y\right)\big|_{(0,0)} = \frac{1}{\lambda i}\iint \frac{E_0\left(x_0,y_0\right)\exp\left(kR_{LS}i\right)r_3}{R_{LS}}dx_0dy_0 \tag{1}$$

Here, $E_0(x_0, y_0)$ represents the light field distribution at the scattering surface, and R_{LS}represents the distance from the lens position to the scattering surface along the optical axis.

In Fig. 1, according to the three-facet Fabry-Perot model [27], the change in threshold gain with light feedback can be expressed as:

$$\Delta g = -\frac{1}{d}\xi\cos\left(\phi_L+\phi_S\right) \tag{2}$$

$$\phi_L = 2kL \tag{3}$$

Where $\xi = \frac{(1-|r_2|^2)r_3}{r_2}$ represents the feedback coefficient (r_1, r_2 represent the reflectivity of laser diode's rear and front face, r_3 represents the reflectivity of target). $\phi_L$is the external cavity phase with optical feedback. $\phi_S = Arg(E(x,y)|_{(0,0)})$ is the phase change of the optical field inside the optical cavity caused by speckle. $k = 2\pi/\lambda$ is the laser wave vector. d and L are the lengths of the inner cavity and the outer cavity of the composite cavity, respectively.

It is known that in a semiconductor laser, the output optical power is proportional to the change of the laser threshold gain. Therefore, the laser light is scattered and re-coupled into the optical cavity, and under weak feedback conditions, we obtain the expression of the modulated output optical power due to the SMI:

$$P \propto -\frac{1}{d}\eta\cos\left(\phi_L+\phi_S\right) \tag{4}$$

Here, let $\eta = u\xi$ [25], $u = |E(x,y)|_{(0,0)}|$ represents the change in electric field amplitude caused by speckle.

When the phase of the external cavity changes 2π, that is:

$$\Delta\phi_L = 2\frac{2\pi}{\lambda}\Delta L = 2\pi \tag{5}$$

From (5), it shows that half a wavelength of the displacement change corresponds to one fringe.

Therefore, the magnitude of the vibration amplitude can be calculated according to the number of SMI fringes between the reversion points:

$$A = n * \frac{\lambda}{2} \tag{6}$$

When the laser is incident perpendicular to the surface of the object to be measured, the autocorrelation property of the periodic signal can be used to realize the rotation speed measurement of a single optical path. The autocorrelation function can be written as:

$$\Gamma_{11}\left(\tau\right) = E\left\langle P\left(\tau_1\right)P\left(\tau_1-\tau\right)\right\rangle \tag{7}$$

τ_1 represents the moment when the light is incident on a certain part of the surface of the object. $\tau = N^+\Delta\tau_s$ denotes the time delay when the light is irradiated at the same point after rotation, where $\Delta\tau_s$ indicates the time for the object rotating one circle in the case of single light path. $N^+$is an any positive integer and is usually set to 1 to simplify calculation. The autocorrelation function is defined as:

$$\Gamma_{11}\left(\tau\right) = \lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{T}P\left(\tau_1\right)P\left(\tau_1-\tau\right)dt \tag{8}$$

When the time delay is equal to the rotation period, that is, when the laser reaches the same point for the second time, the degree of autocorrelation is highest. After derivation and analysis, we get the expression of the object speed:

$$\nu = \frac{l_{rs}}{\Delta\tau_s} \tag{9}$$

Here, l_{rs} represents the arc length of the path the laser travels on the surface of the turntable, which is a complete circumference. In other words, $l_{rs} = 2\pi r_{rs}$, r_{rs} is the distance from the laser spot position to the center of rotation. According to the relationship between linear velocity and angular velocity, (9)

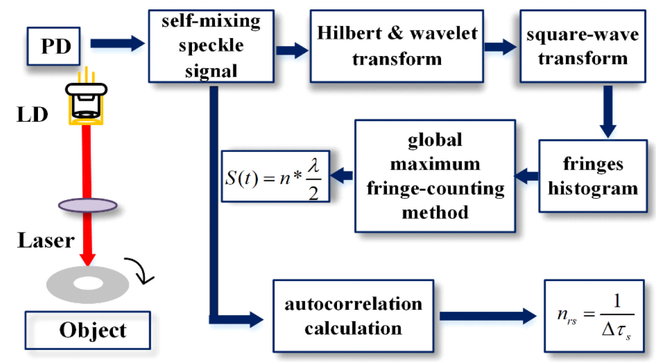

Fig. 2. Flow diagram of the method.

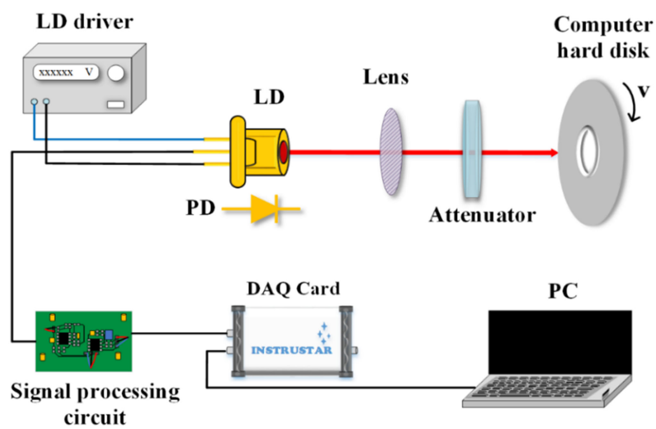

Fig. 3. Setup of the experiment system.

can be rewritten as:

$$\omega_{rs} = \frac{2\pi}{\Delta\tau_s} \tag{10}$$

The flow diagram for performing the proposed single-channel simultaneous measurement of rotation speed and vibration is shown in Fig. 2.

III. Experimental Steps and Results

In order to verify the validity of the proposed method, a series of experiments have been performed, and the experimental device of the system that simultaneously measures rotation speed and vibration is shown in Fig. 3. Computer disk was used as rotating device in the experiment because of its high stability, smooth surface, and high reflectivity. The hard disk, branded by Hitachi, has a maximum speed of 7200 RPM and is attached to an optical shock-proof platform. We use a LD (L650P007) as the light source, driven by a constant current power supply, with an output wavelength of 650 nm, which can emit up to 5mw of light. The LD is fixed on the light level shifter (GCD0401), which is convenient for adjusting the distance of the laser movement accurately. The change of laser power is detected by the power monitoring photodetector (PD) encapsulated in LD, which is converted into current, converted into voltage signal through the impedance sampling circuit, input into the DC module, amplifier and filter, and finally collected by the computer through the data acquisition card (ISDS205A).

First, the angle of the disk and the attenuator are carefully adjusted to achieve a good SMI waveform. We control the speed of the computer disk to ensure that the disk starts to rotate stably, and define the speed at this time as the lowest speed, which is characterized by speed1. By the time, we slightly increase the rotation speed of the computer disk, and define the rotation speed as a lower speed, which is characterized by speed2. We choose to monitor the vibration at 20 mm to the right of the center point of the computer disk, and the experimental results are shown in Fig. 4. The original self-mixing speckle signal collected by the DAQ card in the experiment is shown in Fig. 4(a), and it is obvious that the signal has some fluctuations and sub-peaks. Next, we perform Hilbert transform and wavelet transform on the signal to obtain a smooth SMI signal, as shown in Fig. 4(b). In order to facilitate the judgment of the number of fringes, square-wave transformation is performed on the processed signal, as shown in Fig. 4(c). The position of the reverse point can be judged according to the width of each square wave waveform, and the number of fringes can be judged more accurately and conveniently. Finally, to avoid the misjudgment of the number of fringes caused by the secondary peak and speckle, the distribution bar graph of the number of fringes is drawn, and the global maximum method after excluding outliers is adopted, as shown in Fig. 4(d). We select the value with the largest number of fringes and the number of occurrences, the signal fringe is determined to be 41, and the corresponding vibration amplitude is 13.325 μm ultimately. At the same time, we perform the autocorrelation calculation on the self-mixing speckle signal and get the signal autocorrelation diagram in Fig. 4(e). The period of a signal is expressed as the time interval at which the signal at a non-zero moment is maximally related to itself. Based on this, it is clearly observed in the figure that the rotation period is 0.05087s, and the rotation speed calculated according to $n_{rs} = \frac{1}{\Delta\tau_s}$ is 1179 rpm.

Next, we still select the same laser incident position, control the driving circuit to gradually increase the speed, and define the speed at this time as medium speed, which is characterized by speed 3. The experimental results are shown in Fig. 5. Similarly, Figs. 5(a)-(c) respectively represent the original self-mixing speckle signal collected in the experiment, the smoothed signal after filtering and the signal transformed into a square wave. Fig. 5(d)-(e) represent the fringe histogram and signal autocorrelation graph in this case, respectively. As can be seen from the figure, we determine the signal fringe to be 55, the corresponding vibration amplitude is 17.875μm, the signal period is 0.02415s, and the corresponding disk speed is 2484 rpm.

Further, the laser moves to the right from the center position 15 mm in steps of 5 mm. The SMI signals at positions 15 mm, 20 mm, 25 mm, 30 mm and 35 mm were recorded respectively. In addition, we adjust the driving circuit to measure five groups of speeds, which correspond to the lowest speed, lower speed, medium speed, higher speed, and highest speed, and then number these five sets of speeds and define them as speed 1 to speed 5. Fig. 6 shows the measurement results of rotation

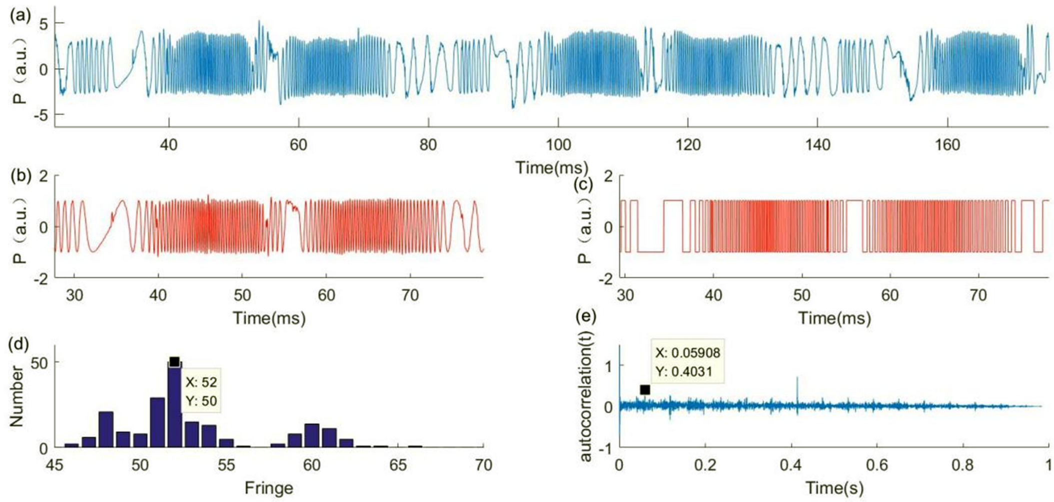

Fig. 4. Experimental results at 20mm with speed2. (a) Original self-mixing speckle signal. (b) Filtered signal waveform. (c) Signal waveform after square-wave transformation. (d) Statistical graph of fringe number. (e) Autocorrelation result of signal.

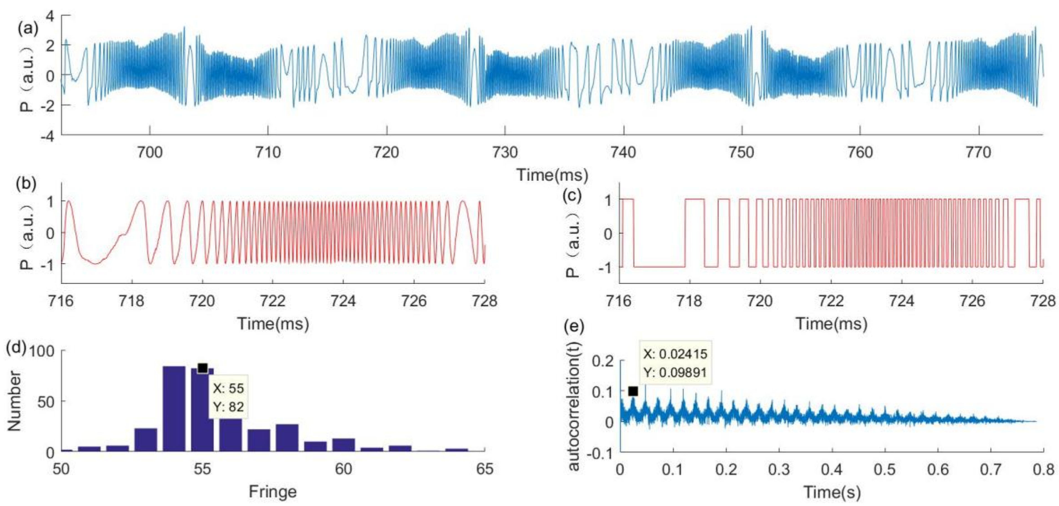

Fig. 5. Experimental results at 20mm with speed3. (a) Original self-mixing speckle signal. (b) Filtered signal waveform. (c) Signal waveform after square-wave transformation. (d) Statistical graph of fringe number. (e) Autocorrelation result of signal.

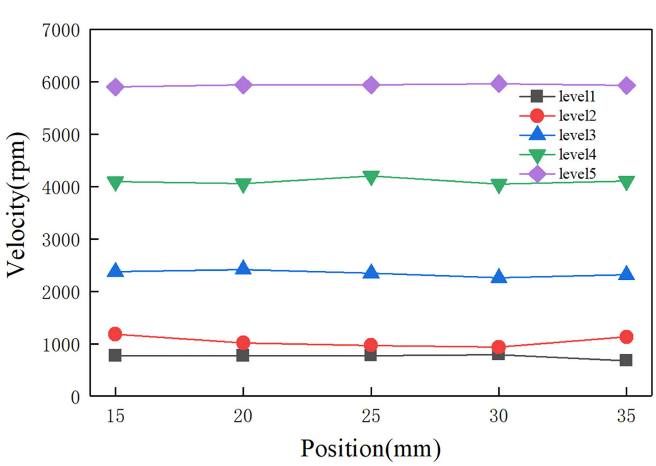

Fig. 6. Measurement results of rotation speed at different positions.

speeds at different positions under these five rotation speeds. It indicates that the measurement results of rotation speed at different positions are very close. Taking the average speed of these five speeds, the calculated speeds 1 to 5 are 758 rpm, 1045 rpm, 2340 rpm, 4100 rpm, and 5935 rpm, respectively. It is verified by experimental results that the vibration amplitude of different positions on the surface of the same rotating object is disparate even if the rotation speed of the object is fixed. In general, the farther the vibration location is from the rotation center of the disk, that is, the closer it is to the edge of the disk, the greater the vibration amplitude of the disk. Fig. 7 shows the results of vibration amplitudes at different positions in five groups of rotational speeds. So far, the experimental results and regularities show that the single-channel rotation speed and vibration measurement scheme based on SMSI is feasible and effective.

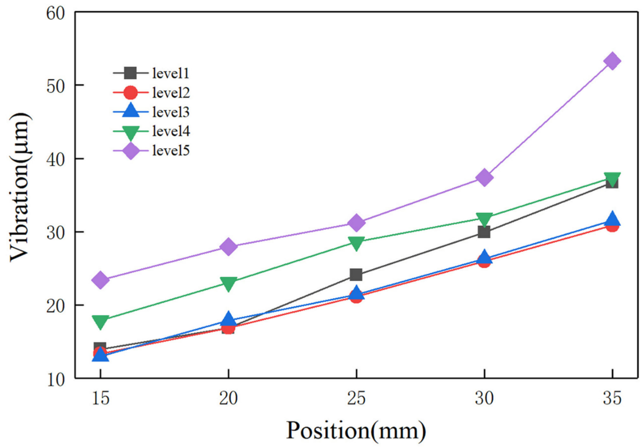

Fig. 7. Vibration measurement results at different positions and different speeds.

IV. Conclusion

In conclusion, a non-contact method for the single-channel simultaneous measurement of rotation speed and vibration by means of self-mixing speckle interference (SMSI) is proposed. The rotation speed is determined by the autocorrelation of SMSI and its mathematical relationship with time delay. Moreover, we develop the signal square-wave transform and global maximum fringe-counting method to measure the vibration caused by the rotation of the object, which improves the efficiency and reliability of the measurement. In the experiment, we employed a computer disk as the object to be monitored and collected the SMSI signals of diverse speeds at different positions. Finally, the experimental results and the regular pattern of vibration amplitude with speed verify the feasibility of this method. Therefore, the proposed method has the advantages of compact structure, simple calculation, and low cost, which makes it particularly important in the fields of non-destructive testing and the quality control in industry.

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