Effect of speckle pattern on laser Doppler velocimeters

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The effect of speckle pattern on laser Doppler velocimeters is studied theoretically and experimentally. We have found that dynamic speckle patterns can cause error in velocity measurement. Increasing sampling time and using proper signal processing circuits can eliminate this bad effect caused by speckle pattern. The accuracy of velocity measurement is better than 2.1% in a wide velocity range (4.66−468.86 mm/s) when speckle effects are taken into account.

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Laser Doppler velocimeter (LDV) is a kind of noncontact remote sensor to determine the speed of a target by means of the Doppler shift of optical beam frequencies. To date, LDVs have been developed with various configurations and used to measure distances, displacements, alignments, and vibrations of remote objects[1−4]. A particular configuration of this kind of sensor is based on the self-mixing effect and utilizes semiconductor laser diodes (LDs) due to their high sensitivity to external optical injection. The typical structure of this sensor is made up with a single-mode LD, a collimation lens, and processing circuit. While external reflector exists outside semiconductor laser, the feedback of a portion of the laser output from a reflecting surface with a lens goes back into the laser cavity. It is amplified and produces a beat note in the output corresponding to the Doppler shift. This phenomenon is usually referred to as self-mixing[5].

Much attention has recently been drawn to the vertical-cavity surface-emitting lasers (VCSELs) interferometer due to its compact, efficient, and low threshold properties[6]. It has also been used as miniature contactless LDV.

The speckle pattern characteristics are discussed in a number of researches. However, only a few studies of self-mixing interference affected by speckle pattern are reported[1].

This paper presents a theoretical analysis of the effect of speckle pattern on LDVs. A comparison between theoretical and experimental results of self-mixing interference is also given. The simulation result of speckle effect on LDVs is reported, and a good agreement has been found in comparison with the experiment. From the results, we have found that dynamic speckle patterns can cause great error in velocity measurement. Increasing sampling time and using proper signal processing circuits can eliminate this effect.

A schematic diagram of a self-mixing interference system is shown in Fig. 1. The system comprised a VCSEL (Unity MCE 8V4C 301) with the wavelength of 0.845 μm and the driving current of 8 mA, a collimating lens, and the external reflector target. The laser emits light which is focused on the moving object by the lens, and the Doppler and speckle signals can be detected by the output of a photo detector (PD) placed inside the laser package for monitoring the output power emitted from the rear end the LD.

It is well known that the reflection of coherent light from a rough surface produces speckle pattern, which is a random interference pattern due to the random nature of the phase perturbations at different positions on the illuminated surface. If the surface is moved, the speckle pattern also moves in the same direction with a proportional velocity[7−10].

In the LDVs, dynamic speckle patterns become the disturbing signal, which will cause error in velocity measurement. Doppler signal is mainly affected by the speckle patterns of image plane in our experimental setup. Schematic diagram of the speckle of image plane is shown in Fig. 2[11,12]. In Fig. 2, (x_i, y_i) and (x_0, y_0) denote the planes of target and conjugate image respectively, and (ξ, η) denotes the diffused surface. N is the normal direction of the diffused surface. $(\theta - \alpha)$ and α are the incidence angle and scattering angle, respectively. The speckle patterns of image plane can be calculated with the Fresnel diffraction theory[11,12]. The amplitude of speckle can be written as

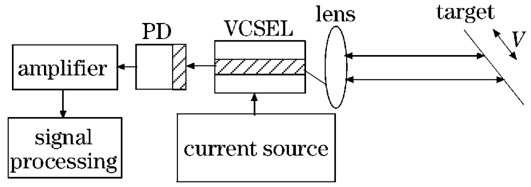

Fig. 1. Schematic diagram of a self-mixing interference system.

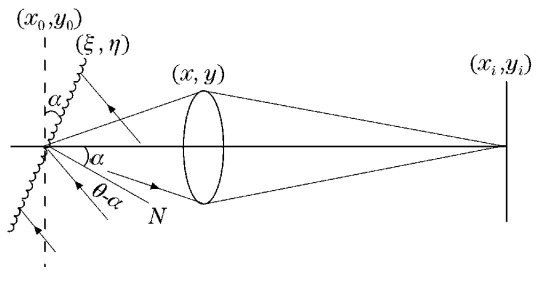

Fig. 2. Schematic diagram of the speckle of image plane.

$$U_i(x_i,y_i)=\int\int_{-\infty}^{\infty}\int\int P(x,y)\exp(-j\frac{2\pi}{\lambda}\Delta r)$$
$$\times\exp\left\{j\frac{2\pi}{\lambda}\left[x_0\sin\theta+(\cos\theta+\cos\alpha)h_0\left(\frac{x_0}{\cos\alpha},y_0\right)\right]\right\}$$
$$\times\exp\left(-j\frac{2\pi}{\lambda}x_0\cos\theta\cdot\tan\alpha\right)$$
$$\times\exp\left\{-j\frac{2\pi}{\lambda z_i}[(x_i-Mx_0)x+(y_i-My_0)]\right\}\mathrm{d}x_0\mathrm{d}y_0\mathrm{d}x\mathrm{d}y, \quad (1)$$

where h_0 denotes the height of scattering cell on the surface and M denotes amplification ratio. λ is the wavelength of the light. h_0 at the position of light spot changes with the movement of target.

Especially, in the LDVs, the incidence angle and scattering angle are the same, as shown in the Fig. 1. $U_i(x_i,y_i)$ has been integrated on the whole pupil plane (x,y) when different directions of the beam are taken into account. So, the amplitude of speckle can be simplified as

$$U_i(x_i,y_i)=\int\int_{-\infty}^{\infty}\int\int P(x,y)\exp\left(-j\frac{2\pi}{\lambda}x_0\tan\alpha\right)$$
$$\times\exp\left\{j\frac{2\pi}{\lambda}\left[x_0\sin2\alpha+(\cos2\alpha+\cos\alpha)h_0\left(\frac{x_0}{\cos\alpha},y_0\right)\right]\right\}$$
$$\times\exp\left(-j\frac{2\pi}{\lambda}x_0\cos2\alpha\cdot\tan\alpha\right)$$
$$\times\exp\left\{-j\frac{2\pi}{\lambda z_i}[(x_i-Mx_0)x+(y_i-My_0)]\right\}\mathrm{d}x_0\mathrm{d}y_0\mathrm{d}x\mathrm{d}y. \quad (2)$$

In the experiment, we placed a piece of white paper under the focused laser beam as target, and the roughness-height information of white paper is observed with a Nextec W1000 WIZ probe laser measurement system, the results are shown in Fig. 3. We can easily find that height and size of the scattering cells on white paper are about $2-20$ μm and $5-47$ μm, respectively.

Based on Eq. (2) and the measured results of height and size of the scattering cells of white paper, we have obtained simulation results of fluctuating intensity of the laser, as shown in Fig. 4. The related parameters used in the above calculation are: $\alpha=30°$, velocity 250 mm/s, the external cavity length 4.1 cm, the radius of lens 3 mm, and the radius of the light spot 80 μm.

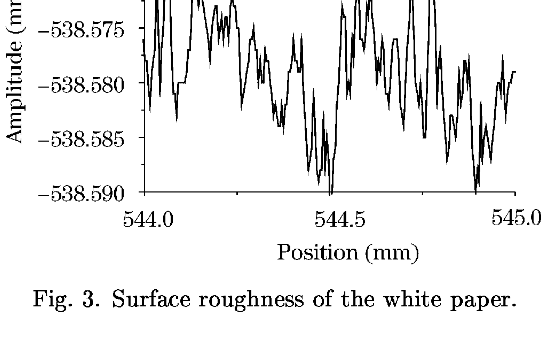

Fig. 3. Surface roughness of the white paper.

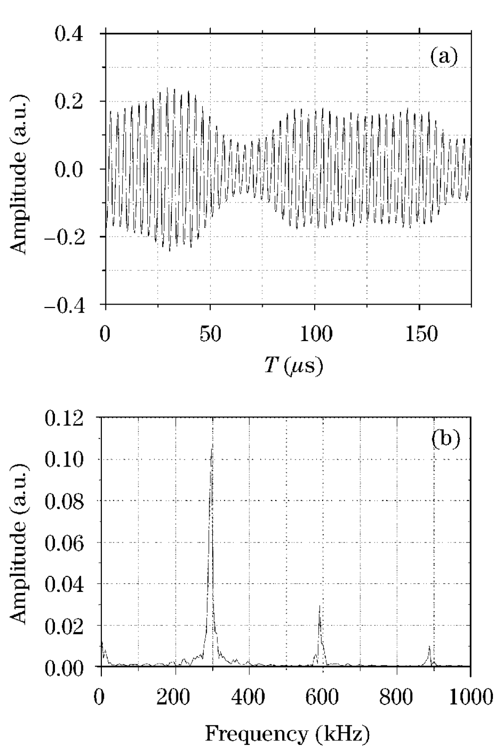

Fig. 4. (a): Simulation results of measurements of the fluctuating intensity; (b): FFT spectrum of the fluctuation measured shown in Fig. 4(a).

As shown in Fig. 4, we have found that Doppler signal was modulated by speckle pattern and Doppler signal broadening. The main peak in Fig. 4(b) is at about 297 kHz which is approximately equal to the theoretical result of 295.8 kHz obtained from

$$f_{\mathrm{D}}=\frac{2V\cos\theta}{\lambda}, \quad (3)$$

where f_{D} denotes the Doppler frequency.

At the same time, the Doppler signal broadening is about 18 kHz. Because the measurement of Doppler frequency is about 297 kHz, the error caused by broadening of speckle pattern is about 6%, which is an intolerant value in velocity measurement.

A typical measurement of the fluctuating intensity of the laser with the photodiode in the laser package is observed with a Tektronix TDS 3052B oscilloscope, the result is shown in Fig. 5(a). A VCSEL with the driving current of 8 mA and the incidence angle of 30° is used in the measurement. Figure 5(b) shows the fast Fourier transform (FFT) spectrum of the fluctuation shown in Fig. 5(a). The modulation of amplitude fluctuation in Fig. 5(a) is Doppler signal but modulated by speckle patterns of image plane, the signal is similar to that predicated by theoretical analysis as shown in Fig. 5(a). Clearly this modulation is slower than the Doppler frequency, resulting in a broadening of the peak at the Doppler frequency in the FFT spectrum shown in Fig. 5(b).

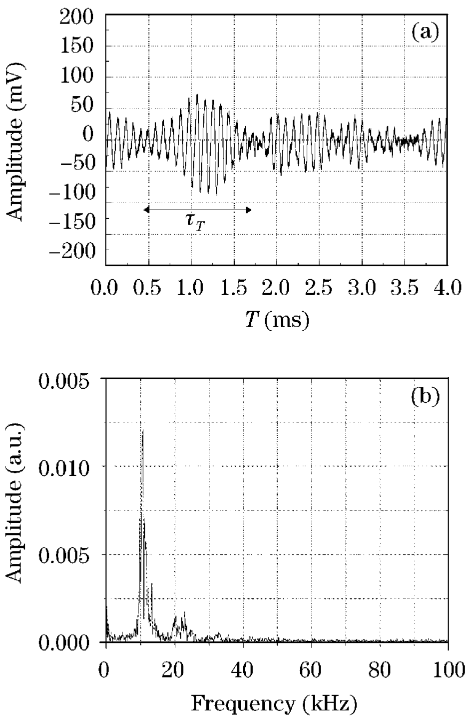

Fig. 5. (a): Typical measurements of the fluctuating intensity of the laser with the photodiode in the laser package; (b): FFT spectrum of the fluctuation measured shown in Fig. 5(a).

For our experimental setup, we can consider that the broadening of Doppler signal is mainly caused by the broadening of transition time[13] which is given by

$$\delta f_{\mathrm{D}} = \frac{2}{\pi \tau_{\mathrm{T}}}, \tag{4}$$

where δf_{D} represents the broadening of Doppler signal, τ_{T} represents transition time. As shown in Fig. 5(a), there are about 10 Doppler signal cycles in one speckle envelope, so

$$\tau_{\mathrm{T}} \approx \frac{10}{f_{\mathrm{D}}}, \tag{5}$$

$$\frac{\delta f_{\mathrm{D}}}{f_{\mathrm{D}}} \approx \frac{1}{5\pi} = 6.4\%. \tag{6}$$

The error caused by the broadening of transition time shown in Eq. (6) is a intolerant value in velocity measurement. So we have to adopt some electronic techniques or others methods to eliminate or reduce this error.

Increasing sampling time is a good method to reduce error of velocity measurement. Figure 6 shows the theoretical error caused by the broadening of transition time with sampling time for measurement of 0.1 s, this sampling time is allowed in many applications. We can see from the figure that the relative error for transition time is below 1.7%.

In signal processing, we use the key technique of phase locking beat frequency for increasing velocity measurement accuracy in wide dynamic range. Phase-locked loop (PLL) can trace the Doppler signal, in the cases of accelerated motion, rapidly changing from rest to motion

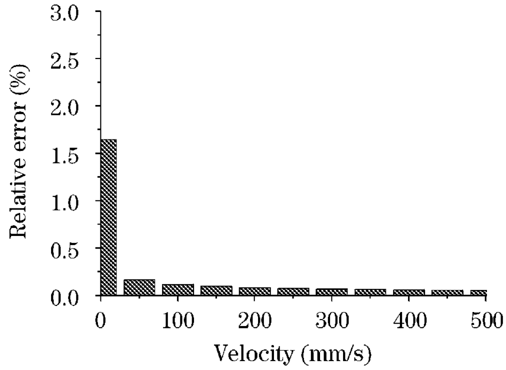

Fig. 6. The theoretical value of relative error of measurement.

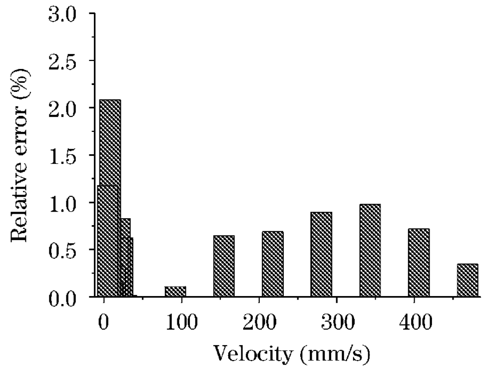

Fig. 7. The relative error of measurement in the experiment.

state, or suddenly changing direction. So, PLL locks and traces the center peak frequency of f_{D}, and the purity of frequency spectrum of Doppler signal is heightened.

The Doppler frequency is observed as shown in Fig. 7 with an Iwatsu FC-8551A frequency counter. We have adopted 0.1 s as sampling time, which can ensure hits density and measurement accuracy simultaneously. But a lot of other factors that reduce measurement accuracy must be mentioned such as vibration, broadening of Doppler signal caused by incident angle and scattering angel, etc.. So, actual measurement accuracy is lower than theoretical measurement accuracy. Figure 7 shows the actual measurement accuracy which is better than 2.1% in a wide velocity range (4.66–468.86 mm/s). From the figure, we can consider that increasing sampling time and using proper signal processing circuits can eliminate the bad effect caused by speckle pattern.

In summary, we have demonstrated that, both theoretically and experimentally, dynamic speckle patterns can cause intolerant error in velocity measurement. The error caused by the broadening of transition time is an intolerant value in velocity measurement. We have found that dynamic speckle patterns can cause error in velocity measurement. Increasing sampling time and using proper signal processing circuits can eliminate this bad effect caused by speckle pattern. The accuracy of velocity measurement is better than 2.1% in a wide velocity range (4.66–468.86 mm/s) when speckle effects are taken into account.

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