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Self-mixing interferometry for rotational speed measurement of servo drives

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Self-mixing interferometry (SMI) is an efficient technique applied to measure distance, velocity, displacement, and vibration. In this work, a compact and low cost SMI is applied to measure the rotational speed of a servo drive up to 6000 RPM. The application of SMI to rotational speed measurement of servo drives instead of the usage of incremental encoders is proposed. The Doppler frequency is obtained via analysis on the power spectral density, which is estimated by the smoothing periodogram method based on the fast Fourier transformation. The signals are processed in MATLAB and LABVIEW, showing that the SMI can be applied to dynamic rotational speed measurement of servo drives. Results of experiments demonstrate that this system is implementable for rotational speed measurement over the whole range from 3 RPM to 6000 RPM. In addition, the system used to measure rotational speed can also accurately record changes in position without integrating the velocity.

OCIS codes: (280.4788) Optical sensing and sensors; (280.3420) Laser sensors; (280.7250) Velocimetry; (120.3180) Interferometry.

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1. INTRODUCTION

Velocity and position are crucial parameters in automotive industry applications. They have become an important topic for servo drives, especially since the drive control is realized digitally. The servo drives contain a threefold cascaded control structure for torque control, speed control, and position control [1], as shown in Fig. 1. Each controller requires a feedback of real value to take control actions properly [1]. While servo drives with analog control use separate sensors to provide the feedback of each control loop (see Fig. 1), those with digital control only need a single sensor, usually a resolver or a high precision optical encoder [2].

A variety of methods have been employed to measure the rotational speed of servo drives. Based on different measurement principles, they can be classified into three categories: magnetic, optic, and capacitive. In general applications, optical encoders are used to get high resolution and high accuracy. The number of lines of optical encoders is significantly higher than that of magnetic encoders, and it is easy to realize 10,000 or even 50,000 lines per revolution for optical encoders. Yet, just as for other encoders, the interpolation should be applied to increase the resolution in order to provide a sufficient speed signal. In addition, the cost of optical encoders is quite high, especially encoders with a very high resolution. Except for interferometric sensors, other methods are all based on pole or tooth counting, which provides periodic analog signals and enhances the resolution by interpolation [1]. Instead of relying on the teeth or poles of the object, interferometric sensors obtain measurement parameters by interfering with their intrinsic wavelengths; thus, they have an inherently high resolution and accuracy. A well-known interferometric technique for velocity measurement is laser Doppler velocimetry (LDV) [3], which can easily get a quite high resolution and accuracy. LDV has been widely applied in fields of classical mechanics, modal analysis, on-line quality control, and medicine [4]. However, LDV still suffer several disadvantages. The major drawbacks are the high cost and a large size resulting from a complex optical system of sensing heads. The interferometric encoder applied to servo drives has been reported in [2], where LDV was employed. The technical results obtained from experimental setups are quite encouraging. However, LDV does not solve the cost issue, cutting cost down to an acceptable range for servo drive applications.

With a continual drive to more precise control, smaller feature sizes, and lower costs, there has been a growing interest of laser self-mixing sensors. In comparison with the traditional LDV, self-mixing interferometry (SMI) simply consists of a laser diode, a focusing lens, a target for test, and related electronics for extracting the self-mixing signals without any additional or complicated optical components. The first significant feature of such SMI is that this technique allows the laser to perform as both a light source and a detector, and possibly offers the

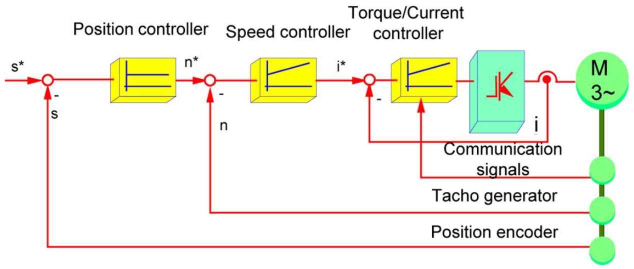

Fig. 1. Basic structure of servo drive, showing the feedback control loops of a position controller, a speed controller, and a torque controller.

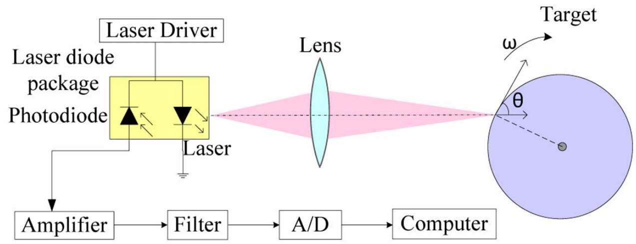

Fig. 2. Schematic model of self-mixing sensor applied for rotational speed measurement.

advantages of a lower cost, fewer components, and a self-aligned system for a variety of applications such as velocity measurement for solids and liquids [5–8], displacement construction [9–11], absolute distance measurement [12,13], and vibration detection [14–16]. The theory and application of SMI were introduced in detail in [17–19], and an overview of instrumentation and measurement developed from the concept of SMI was presented in [20,21]. Generally, the optical feedback is an unavoidable consequence of involving a laser. The first report of velocity measurement with the self-mixing technique in a gas laser was published by Rudd [22], whereas in the first report [23] in 1978, both the amplitude modulation and frequency modulation of SMI were demonstrated. With a fast development of laser technology, numerous preliminary applications for velocity measurement with laser diodes instead of gas lasers have been reported [4,6,24]. Another important character of SMI is that the fringe shift caused by the feedback light is related to the amount of displacement [25]. Therefore, SMI can also be applied to measure changes in the position of servo drives without integrating velocity, and such a feature makes SMI an ideal alternative to incremental encoders in servo drives.

2. OPERATING PRINCIPLE

The effects of optical feedback in semiconductor lasers have been studied since 1980s; a milestone paper, which proposed the rate equation mode [26] of a semiconductor laser under optical feedback, has been published by Lang and Kobayashi in 1980. It illustrated that the dynamical changes in the carrier density of a semiconductor laser due to optical feedback lead to a modification of the refractive index, which in turn changes the resonant frequency of the laser [17]. Optical-feedback effects of semiconductor lasers are frequently used for a variety of application, including self-mixing, intermittency, and chaos [27].

The schematic model of a self-mixing sensor applied to rotational speed measurement is shown in Fig. 2. The light beams emitted from the laser diode are focused by the lens and then strike the target. The feedback light scattered by the target surface injects into the laser cavity, superimposes on the existing internal field, and modulates both the amplitude and frequency of the lasing field. The static characteristics of semiconductor lasers with optical feedback can be theoretically investigated with the relationships among the reflectivity of the internal cavity and external reflector, the gain in a medium, and other static laser parameters [19]. The self-mixing signal is simply obtained by observing the laser output power with the integrated photodiode [28] or by recording the terminal voltage [29], which further simplifies the configuration of self-mixing sensors. Throughout of this study, a commonly used current signal from a photodiode is used as the source of self-mixing signals. When the light beams strike the target, the backscattered light injects into the laser cavity and changes the frequency and the amplitude of the laser. The output power of the laser is modulated by a frequency f_D, which is related to the linear speed by the following equations:

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

$$v = 2\pi r\omega, \quad (2)$$

where λ is the wavelength of the laser diode, v is the linear speed of the target, θ is the angle between the moving direction of the target and the incident direction of the laser beam, and r and ω are the radius and rotational speed of the target, respectively. Based on Eq. (1), the speed is linearly proportional to the frequency of the self-mixing signal as the angle θ and the wavelength λ are constant, which suggests that a sensor monitoring Doppler frequency could be used to calculate the speed. The Doppler frequency can be estimated from an analysis of its spectrum, and the most classical method is the periodogram, which is given by a modulus squared of the discrete Fourier transform.

3. EXPERIMENT

The sensor head applied to measure the rotational speed of servo drives simply consists of a commercial 785 nm laser diode, a lens, and a preprocessing circuit. Figure 3 shows the measuring system. As the surface of the motor shaft is not ideal, it can be used as a scattering surface, which can make the SMI a rather simple sensor unit. The laser beam is focused at a fixed point on the motor shaft, and the distance between the sensor head and shaft is 4.9 mm. The experiment is implemented without the use of a laser diode temperature controller, with the aim of reducing sensor cost and power consumption. Nevertheless, further work is needed to develop an effective method to maintain the performance of the sensor without temperature stabilization in a wide range of ambient temperatures, for instance, by tuning the laser current according to a certain model [30].

To acquire a good velocity reference, the servo drive is operated at a constant rotational speed controlled by the feedback of a 21 bit optical encoder. It is found that to acquire proper signal, several parameters should be optimized, such as the distance between the sensor head and the motor shaft, the noise of the amplifier, and the focal position of lens. The self-mixing

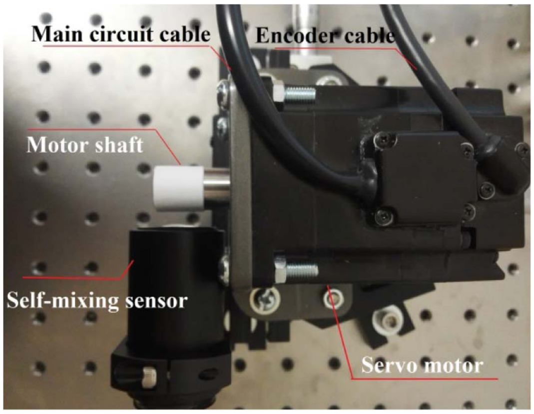

Fig. 3. Labeled photograph of the measuring system.

signal modulated by the backscattering light is acquired by tracing the small variations of optical power with the built-in photodiode. After converting the current signal into voltage with a current to voltage convention circuit, the DC component of the signal is removed by a high pass filter and the weak signal is amplified by a low noise amplifying circuit. Then the amplified analog signal is digitized for further processing in a computer with MATLAB or LABVIEW to extract the Doppler frequency.

For general application, the maximum rotational speed of servo drives is set to be 6000 RPM. The minimum rotational speed is 3 RPM since the servo drive used is controlled with the software provided by the motor manufacturer. Therefore, the measurement of rotational speed is performed over the range of 3–6000 RPM. The test results show that the measuring range is not limited by the response frequency of the photodiode but by the signal processing circuit, especially the bandwidth of the amplifier. A potential approach to overcome this problem is to increase the angle θ between the moving direction of the motor shaft and the incident direction of the laser beam, which will result in a decrease of the $\cos(\theta)$ term in Eq. (1), giving a lower Doppler frequency. Once the stable rotational speed measurement system is established, the same system can also be applied to measure the changes in position of motor with only a change of the signal processing method, instead of depending on the speed integral.

Figure 4 shows several typical self-mixing signals in the time domain. During experiment, it is found that the servo drive causes strong interference to the acquired self-mixing signals.

The self-mixing signal in Fig. 4 is distorted by a multiplicative noise caused by the speckle effect since the rough surface of the motor shaft backscattered the coherent light of the laser diode [31–33]. This results in random amplitudes, leads to some loss of ideal waveform of the signal, and broadens the spectrum, ultimately affecting the measurement result. Meanwhile, the servo drive causes serious interference to the output signal, which can be seen clearly from the signal of 3 RPM, which has a strong noise.

Figure 5 shows the corresponding power spectral density (PSD) of the time domain signals with a simple periodogram method based on the fast Fourier transform (FFT). To accurately extract the Doppler frequency, the PSD estimation with the periodogram method must be smoothed or fitted [29,34,35].

Extracting the Doppler frequency corresponding to the speed is done by finding the frequency at which the peak point

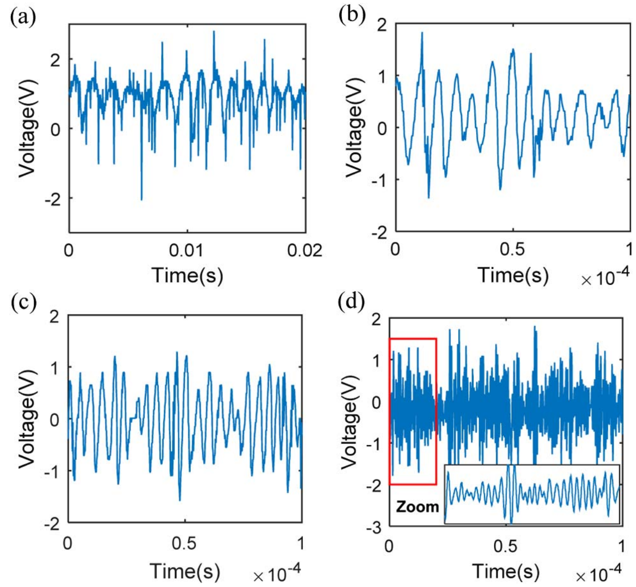

Fig. 4. Time domain self-mixing signals of different rotational speed; the rotational speed of (a) is 3 RPM, (b) is 500 RPM, (c) is 1000 RPM, and (d) is 6000 RPM. Note that the time duration of (a) is different from (b)–(d).

of PSD corresponds to the maximum. However, the presence of two types of noise, additive noise and multiplicative noise [4], broadening the spectrum makes the estimation of the Doppler frequency more difficult. It is noticed that the signal of rotational speed 3 RPM has the minimum spectral broadening, while the signal of rotational speed 6000 RPM has a large spectral broadening since the broadening is proportional to the measuring velocity [16].

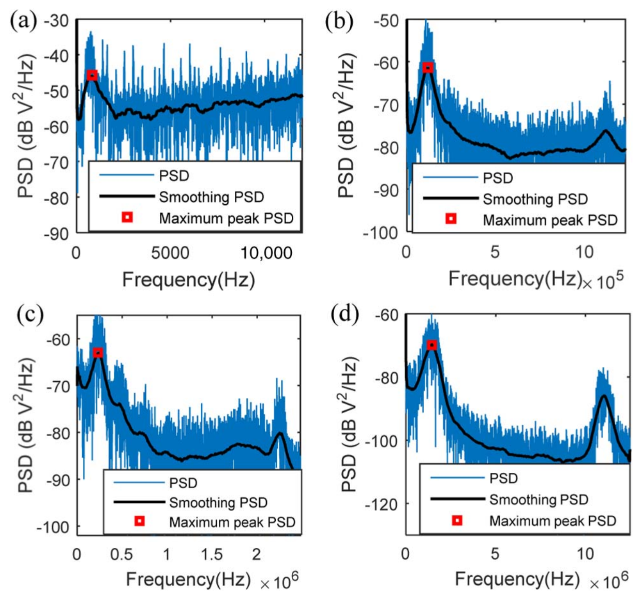

Fig. 5. PSD of self-mixing signal; the rotational speed of (a) is 3 RPM, (b) is 500 RPM, (c) is 1000 RPM, and (d) is 6000 RPM. Blue lines are PSD based on the periodogram, black lines are the smoothing PSD, and red squares are the maximum peak PSD corresponding to the Doppler frequency.

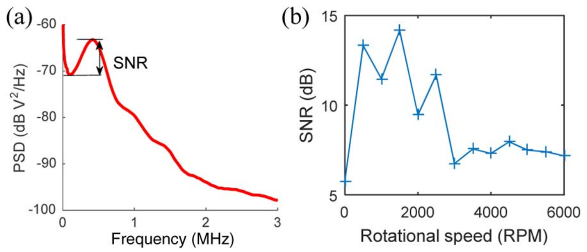

Fig. 6. SNR performance of self-mixing signals; (a) is an example of PSD showing how the SNR is determined by measuring the difference between the maximum peak of PSD and the noise floor. (b) is the measured SNRs versus rotational speed.

The signal-to-noise ratio (SNR) of the self-mixing signal is of great interest for SMI. After getting the PSD, SNRs can be directly obtained at different speeds by measuring the difference between the maximum PSD and the noise floor, as shown in Fig. 6(a). Figure 6(b) shows the SNRs of different rotational speeds. Each SNR is the average of eight SNRs obtained based on the measuring method in Fig. 6 from eight experiments. For rotational speed measurement of servo drives, the SNRs of the signal depend on the strength of SMI signals and the noises of the laser, electrical circuit, and environment. During the experiments, the major environmental noise is from the vibration of the motor and the electromagnetic noise, which can be eliminated by an electromagnetic shield. The presence of multiplicative noise and additive noise decreases the strength of signals, leading to a loss of signal and broadening the PSD. It can be seen that the SNR is 6 dB at 3 RPM and increases to 13 dB at 500 RPM. However, the SNRs decrease to 7 dB when the motor runs faster than 2500 RPM.

Figure 7(a) shows the relationship between the Doppler frequency and the rotational speed, and Fig. 7(b) shows the relationship between the measured rotational speed and the reference rotational speed. According to Eq. (1), the Doppler frequency is linear to the rotational speed. However, the mechanical errors, the nonzero linewidth of the laser, and the spectral broadening of the signal affect the measuring results. The nonzero linewidth of the laser was proved to have a negligible effect on the Doppler frequency in [36]. The presence of the speckle effect introduces an undesired modulation frequency, which is related to longitudinal speckle sizes of the virtual speckles projected on the target side [18,37] superimposed

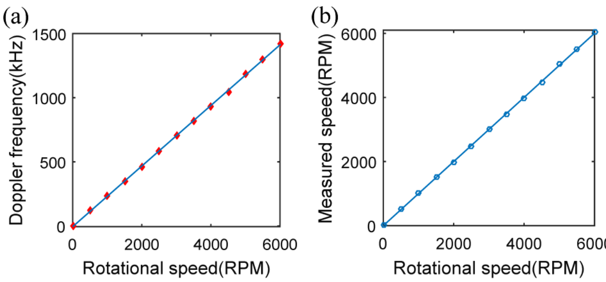

Fig. 7. (a) Doppler frequency of self-mixing signal versus rotational speed. The blue line is obtained by the best fitting of the experimental data. (b) Measured rotational speed versus reference rotational speed. The blue line is obtained by the best fitting of the experimental data.

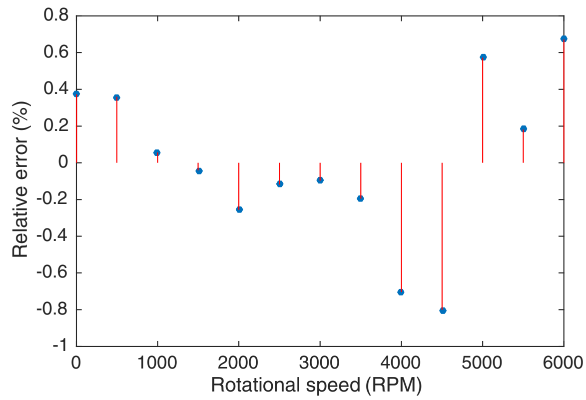

Fig. 8. Relative error versus rotational speed. The relative error is defined as the absolute error divided by the span, and the blue spots represent the relative errors.

to the self-mixing signal. The longitudinal speckle dimension is $S_l = \lambda s^2/w^2$ (where λ is the wavelength of the laser, w is the spot size on the target, and s is the target–laser distance) [18]. By optimization of the parameters w and s, the modulation frequency due to speckle effect could be reduced but never eliminated.

The relative error [38,39], which is defined as the absolute error divided by the span in this case, is exhibited in Fig. 8. It is found that the relative error over the usable speed range is less than 1%. Based on the analysis above, the SNR decreases with the increment of speed. The accurate measuring of high rotational speed is hampered by the decreased SNR resulting from the PSD spreading over a large range.

The dynamic measuring system is set up with LABVIEW, which has the same signal processing flow as that in MATLAB. The measurement of rotational speed is also performed over the range of 3–6000 RPM. Figure 9 shows the relative error obtained by varying rotational speed over 30 s. It can be seen that the dynamic measuring relative error is within 5%, showing that SMI can be applied to rotational speed measurement of servo drives for dynamic measurement. The black dotted line in Fig. 9 represents the rotational speed 2500 RPM, after which the relative error is greatly impacted by time. Compared to the SNRs in Fig. 6(b), it is noticed that the SNRs of the SMI signal decrease to 7 dB when the rotational speed is faster than 2500

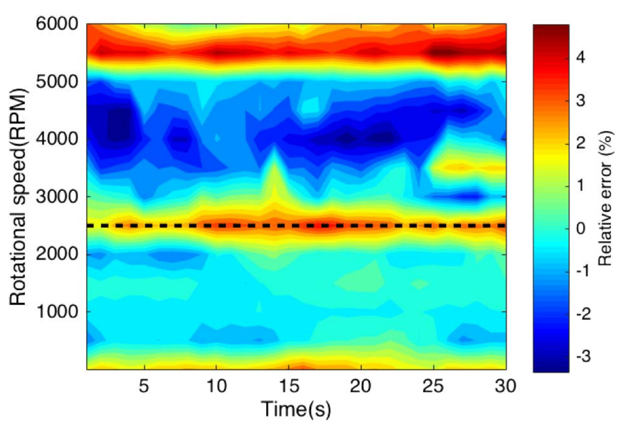

Fig. 9. Relative error obtained by varying rotational speed over 30 s. The black dotted line represents the rotational speed of 2500 RPM.

RPM. This demonstrates that the SNR of the signal greatly affects the stability of the test results. Further work is in progress to improve the test results of dynamic measurement [40].

4. CONCLUSION

In this paper, SMI is employed to measure the rotational speed of servo drives. A small size, light weight, and low cost are the main characteristics of this rotational speed sensor. For the first time to our knowledge, the application of SMI for rotational speed measurement of servo drives is proposed to replace the incremental encoder. The experiment apparatus is built to validate the feasibility of rotational speed measurement of servo drives with SMI. The Doppler frequencies are acquired based on the simple smoothing periodogram PSD estimation method. The results of experiments demonstrate that SMI is applicable to measure to rotational speed of a servo drive up to 6000 RPM or even higher with a relative error within 1% over the whole speed range. Meanwhile, the results also exhibit that the SNRs of SMI signals decrease at high speed. Moreover, the signal processing in LABVIEW is established to verify its feasibility in dynamic measurement of rotational speed and the test results indicate that the relative error is within 5%. In addition, the system provides related applications such as measuring position changes of motors only with a change of the signal processing method. Therefore, the SMI could cut the cost down to the level suitable for servo drives, even much cheaper than optical encoders.

In further work, other methods to determine the Doppler frequency will be developed to improve the performance and processing speed. Meanwhile, the hardware part should be modified to obtain small size and make it suitable for real application. In addition, the signal processing method of SMI used to measure the changes in position will be explored. This could lead to the application of SMI in drive system, and it could potentially be a good alternative to optical encoders.

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