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Measuring millimeter-scale distances in a laser self-mixing velocimeter with low-speed wavelength modulation

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ABSTRACT

A method is proposed to measure short distances using a laser self-mixing velocimeter with low-speed wavelength modulation (2 kHz). The two power spectra obtained in the frequency domain around the rising edge and the falling edge frequencies are employed for estimating the distance and the velocity of a target. The results show that a low-speed wavelength modulation is helpful for the measurement because there are not enough fringes at such distances. The noise caused by the low-speed wavelength modulation and short distances can be distinguished by power spectrum analysis. The distance measurement attains a relative standard deviation of around 10^{-3} in the range from 1 mm to 23 mm, and a relative standard deviation of around 10^{-4} is obtained in the velocity measurement.

1. Introduction

Laser self-mixing velocimetry is a simple and low-cost self-aligned optical sensing technique that has been widely adopted for measuring the velocity of moving targets based on the Doppler effect [1–6]. Laser self-mixing interference is generated in the laser cavity itself, induced by the reflective or back-scattered light caused from the surface of an external target. The laser emission power changes periodically, and the spectrum of the laser emission power waveform resides around the Doppler frequency f_D relative to the target speed and the fixed laser wavelength. The velocity is retrieved from the Doppler frequency, which is observed in the frequency domain as a single power spectrum around the Doppler frequency [7–11]. In addition to the velocity, the distance to a target must also be measured in many instances, such as optics fabrication, products' shape tests. Laser interferometry is generally employed for measuring the distance of specular reflective or cooperative targets. However, laser self-mixing interferometry can be employed to retrieve the distance information of diffuse reflective or non-cooperative targets by means of laser modulation [12]. Norgia [13] reported a real-time self-mixing interferometer for long distances. Guo and Wang [14] reported a self-mixing interferometry based on a double-modulation technique for absolute distance measurement. Here, when the laser wavelength λ is modulated by a regular periodic function, changes in the laser power are related to the distance between the laser and target, and it is possible to retrieve this distance information. For optimizing the laser self-mixing signal, a continuous triangle function is selected as the modulation signal, which acts on the laser current to alter the value of λ. The application of laser self-mixing interferometry has been generally reported for conducting measurements of velocity [15] and distance [16], respectively, but not simultaneously. In contrast, Norgia [17] reported a simultaneous measurement of the distance and the velocity. Here, quite long distances from 15 cm to 1 m were measured using high-speed wavelength modulation (40 kHz). However, the measurement may not be effective on condition of shorter distances, such as millimeter-scale distances. Because such millimeter-scale distances may not provide a sufficient number of fringes, besides, the noise associated with speckle patterns may obscure the self-mixing signal.

In this paper, a laser self-mixing single-channel interference approach using low-speed wavelength modulation is proposed for simultaneously measuring the millimeter-scale distances and velocities of a rotating disk. The two power spectra of the modulated self-mixing signal are obtained around the rising-edge and falling-edge frequencies, rather than the single power spectrum obtained without modulation. We use low-speed wavelength modulation (2 kHz) instead of high-speed modulation to conduct the measurement by means of spectrum analysis. The method of spectrum analysis is selected to distinguish the noise associated with speckle patterns which may obscure the self-mixing signal.

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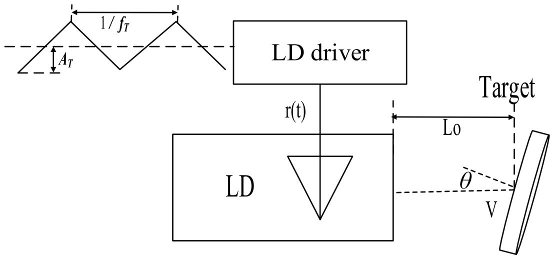

Fig. 1. Schematic of the measurement principles.

2. Principles

The laser self-mixing interference is based on the principle of external feedback and the establishment of a stable interference must meet the amplitude and the phase conditions. Under weak feedback level, the emission power $P(t)$ versus time t is obtained as

$$P(t) = P_0[1 + m\cos(2\pi\upsilon\tau_L)] = P_0[1 + m\cos(4\pi\upsilon_c \frac{L_0 + Vt\cos\theta}{c})] \tag{1}$$

where P_0 denotes laser free power, V denotes the target velocity and θ denotes the incident angle of light, L_0 denotes the distance in Fig. 1, υ_c denotes the light frequency, m denotes a mismatch between the reflected and the lasering modes, and t denotes time.

The function above is cosine-like, the period of which can be deduced via the derivative of the polynomial in the brackets; thus, it can be expressed as

$$\frac{\partial}{\partial t}(4\pi\upsilon_c \frac{L_0 + Vt\cos\theta}{c}) = \frac{4\pi}{c}\frac{\partial}{\partial t}(\upsilon_c L_0 + \upsilon_c Vt\cos\theta) = 2\pi(f_s \pm f_D) \tag{2}$$

where f_s is the frequency shifting resulting from the target distance and f_D denotes the Doppler frequency resulting from the target velocity.

Both f_s and f_D are deduced separately to obtain their expressions of each other. In the case of f_D based on the Doppler effect, the light frequency υ_c is equal to the light frequency υ_{c0} of without modulation; thus,

$$2\pi f_D = \frac{4\pi\upsilon_{c0}}{c}\frac{\partial}{\partial t}(Vt\cos\theta) = \frac{4\pi\upsilon_{c0}}{c}V\cos\theta = \frac{4\pi}{\lambda}V\cos\theta, \tag{3}$$

then

$$f_D = \frac{2}{\lambda}V\cos\theta. \tag{4}$$

In the case of f_s, the light frequency υ_c is modulated following

$$\upsilon_c(t) = \upsilon_{c0} + \eta r(t), \tag{5}$$

where η denotes the modulation coefficient of light frequency, and r(t) denotes the modulation function in Fig. 1, the amplitude of which is A_T and the frequency is f_T. The slope of r(t) is $2A_T f_T$ when the symmetry of the modulation function is 50%; thus,

$$\begin{aligned} 2\pi f_s &= \frac{4\pi L_0}{c}\frac{\partial}{\partial t}\upsilon_c(t) = \frac{4\pi L_0}{c}\eta\frac{\partial}{\partial t}r(t) \\ &= \frac{4\pi L_0}{c}\eta\frac{2A_T}{1/f_T} = \frac{8\pi L_0}{c}\eta A_T f_T. \end{aligned} \tag{6}$$

And then

$$f_s = \frac{4L_0}{c}\eta A_T f_T. \tag{7}$$

The frequencies of the experimental signal are the results of f_s and f_D, but the sign of the slope of r(t) is positive or minus when r(t) varies. Thus, the increasing and decreasing amplitude of the periodic modulation function produces spectra centered around the rising edge and the falling edge frequencies of υ_1 and υ_2, which are given as

$$\upsilon_{1,2} = \pm f_s + f_D, \tag{8}$$

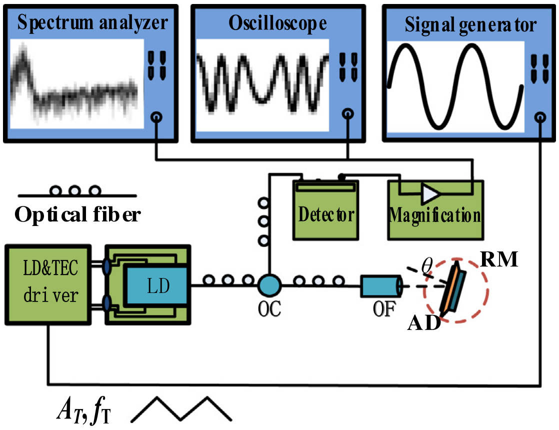

Fig. 2. Schematic of the experimental system (LD&TEC driver: laser diode driver and thermal energy converter; LD: laser diode; OC: optical coupler; OF: optical focuser; AD: aluminum disk; RM: rotation machine).

where υ_1 pertains to "+" and υ_2 pertains to "−". The values of V and L_0 are derived as follows:

$$V = \lambda(\upsilon_1 + \upsilon_2)/(4\cos\theta) \tag{9}$$

$$L_0 = c(\upsilon_1 - \upsilon_2)/(8\eta f_T A_T) \tag{10}$$

where υ_1 and υ_2 are obtained from the experimental spectrum and λ denotes the laser wavelength without modulation.

3. Experimental setup

The experimental design in Fig. 2 employed optical fibers to decrease the environmental noise, and includes the laser diode (LD, FRL15DCWD-A81-1550-C model, 1550 nm, 20 mW), the laser driver, the signal generator, the fiber splitter (OC), the photoelectric detector, the oscilloscope, the magnification and a spectrum analyzer. The fibers employed in the experiments are all single mode. The laser self-mixing interference was generated under weak feedback level.

The LD is driven by the laser diode and thermal energy converter (LD&TEC, ITC110, Thorlabs), which provides the modulation current driven by the function obtained from the signal generator, which continuously modulates the value of λ. The typical modulation amplitude A_T is equal to 400 mVpp and frequency f_T is equal to 2 kHz for optimizing the measurement. The modulation coefficient of laser power β is about 25.4 mW/V and the modulation coefficient of light frequency is about 200 GHz/V. As the LD is modulated, the injection current is about 350 mA (1.7 V) varying by an amplitude of 80 mApp. The light is split into two components using the fiber coupler with a splitter ratio of 50:50. One component irradiates a rotating aluminum disk (AD) target at an incident angle $\theta = 20°$, and the back-scattered light (about 4%) passes through the original path back to the laser cavity for generating laser self-mixing interference. Meanwhile, the other component is monitored by the photoelectric detector, and the laser self-mixing interference is analyzed by the spectrum analyzer after first undergoing a magnification process.

4. Results and discussion

As the experimental signal in the time domain is continuously periodic, the frequency spectrum of the self-mixing signal can be transformed via a FFT (fast Fourier transform) [18], which samples the signal and divides it into its frequency components. We immediately use the FFT to obtain the power spectrum of the self-mixing signal by a spectrum analyzer. The integral of the real-time signal's squared modulus is equal to the integral of the squared modulus of its frequency