A Laser Self-mixing Interference Vibrometer Based On Current Modulation and DSP Demodulation

Wei Xia, Ming Wang*, Wenhua Guo
Department of Physics, Nanjing Normal University, Nanjing 210097 , P. R. China

ABSTRACT

The modulation and demodulation technique of laser self-mixing interference vibrometer is researched in this paper. Combining with triangular current modulation and DSP demodulation technique, a new-type laser self-mixing interference vibrometer is designed to achieve non-contact vibration measurement of a target. Theoretical analysis, simulation results and error evaluation are presented in this paper. The vibration waveform is reconstructed with an accuracy of 0.325 micron in a wide dynamic range. Experiments results show a good agreement with the simulative results. The vibrometer is compact, inexpensive, self-aligning and can be applied to various vibration measurements for its simplicity.

Keywords: self-mixing interference, vibrometer, DSP technique

1. INTRODUCTION

Laser self-mixing interference(SMI) [1-3] is a viable technique for geometrical parameters measurement. A laser beam emitted from a diode is reflected or scattered by a target. Then the reflected light re-enters the laser cavity and mixes with the original light to produce a self-mixing interference effect. The SMI signal which carries the movement information of the irradiated target is suitable for parameter measurement of velocity, distance, vibration and displacement [4-6].

It has been confirmed that the vibration of a loudspeaker can be measured by using of a self-mixing laser diode[7]. However, the demodulation method of the above-mentioned vibrometer utilizes the asymmetry of the sawtooth-like self-mixing signal which is much sensitive to feedback strength and noises induced by surrounding environment to decide the moving direction of a target. A compact triangular current modulation vibrometer employing a self-mixing interference diode is proposed. The principle of vibration measurement is based on time integration of each sampled displacement measured during every modulation period. The moving direction of the target is implied in the sign of each sampled velocity and the vibrometer is immune to the noise induced by environment. DSP based signal processing unit makes the vibrometer inexpensive and potable, so the vibrometer can be applied to various vibration measurements for its simplicity.

* wangming@njnu.edu.cn; phone 86-025-83598685; fax 86-025-83598685.

Optical Metrology and Inspection for Industrial Applications, edited by Kevin Harding, Peisen S. Huang, Toru Yoshizawa,
Proc. of SPIE Vol. 7855, 78551U · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.870264

2. SELF-MIXING INTERFERENCE VIBROMETER WITH TRIANGULAR CURRENT MODULATION

2.1 Schematic Configuration of a Vibrometer System

Schematic configuration of optical path and some main functional blocks of a vibrometer is shown in Fig. 1.

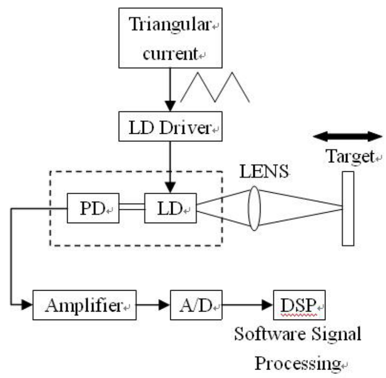

Figure 1.Schematic configuration of a vibrometer system.

A laser diode(LD) is wavelength and intensity modulated by a triangular injection current. The light beam emitted from a LD is focused onto a vibrating target (a loudspeaker). Part of reflected light returns to the laser cavity, mixes with the original light, and generates mode hop signal superposed on the triangular light intensity. The output power of the light is detected by a monitoring photodiode(PD). The signal from PD is sampled and converted into a digital signal by an A/D convertor and sent to a digital signal processor (DSP) to reconstruct the vibration waveform of the target.

2.2 Operating Principle

The principle of the vibration measurement is shown in Fig. 2. M1 and M2 are reference plane and vibrating plane, respectively. A triangular injection current which is fed to a self-mixing laser diode is shown in Fig. 2(a). Fig. 2(b) shows the correspondent output power of the light with a time dependent position of M2.

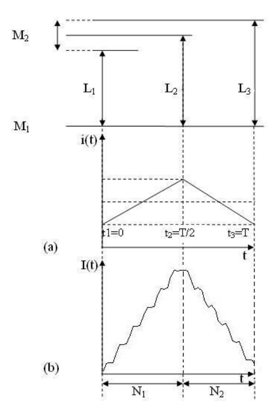

Figure 2. Principle of the vibration measurement. (a) A period of triangular injection current

(b) A correspondent SMI signal obtained from PD

The resonance condition of the external cavity composed by M1 and M2 is $L = m \times \lambda / 2$. Where L is the length of the external cavity; λ is the wavelength of the laser; m is an arbitrary integer. Actually, the mode hops produced during the up- and down-slope of a triangular modulation period due to the wavelength modulation are symmetrical. Therefore, the difference of the counted numbers of the mode hops during each up- and down-slope of the triangular modulation period is only yielded by the variation of the length of the external cavity. N_1 and N_2 denote the numbers of mode hops counted during the up- and down- slope of a triangular modulation period, respectively. Then the displacement of M2 during one modulation period is given by,

$$L_3 - L_1 = \lambda/2 \times (N_2 - N_1) = \lambda/2 \times \Delta N \tag{1}$$

Compared with a self-mixing laser diode driven by constant current, complex algorithm for discriminating a positive or negative direction of movement is no more needed because the moving direction of the vibration is implied by the sign of the value of $N_2 - N_1$, which can be either positive or negative. Since the number $\Delta N = N_2 - N_1$ is proportional to the displacement in one modulation period, we can obtain the displacement by integrating ΔN in each modulation period. Therefore, the total displacement of the target can be written as follows,

$$\Delta L = \lambda/2 (\Delta N)_1 + \lambda/2 (\Delta N)_2 + \cdots \lambda/2 (\Delta N)_n = \lambda/2 \sum_{i=1}^{n} (\Delta N)_i \tag{2}$$

2.3 Algorithm Simulation and Error Analysis

The value of the parameters in simulation are as follows,

1. The frequency of the triangulation current is 4 KHz with 2 mA peak amplitude.
2. The displacement of the target is written as $s(t) = 3.1 \times 10^{-3} \times \cos(400\pi t) mm$.
3. The initial length of external cavity is 12 cm.

We can extract the displacement of the target using eq. (2). Since the ratio between modulation frequency and vibration frequency is 20:1, we will have 20 modulation periods in a vibration period. As a result, we will reconstruct a period of the vibration using 20 measurement points. A typical SMI signal, a sinusoidal vibration waveform and a reconstructed vibration waveform are shown in Fig. 3(a), Fig. 3(b) and Fig. 3(c), respectively.

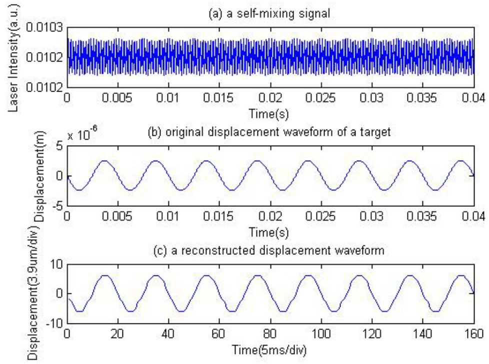

Figure 3. algorithm simulation: (a) a typical SMI signal; (b) a sinusoidal vibration waveform; (c) a reconstructed vibration waveform.

From Fig. 3, the reconstructed vibration waveform agrees well with the original vibration waveform. Fig. 4(a) shows the distribution of discrete measurement points on the original vibration waveform and the periodic error is shown in Fig. 4(b). Measurement error is small at most points except the peak position of the vibration and the maximum error is less than 0.3 micron limited in theory.

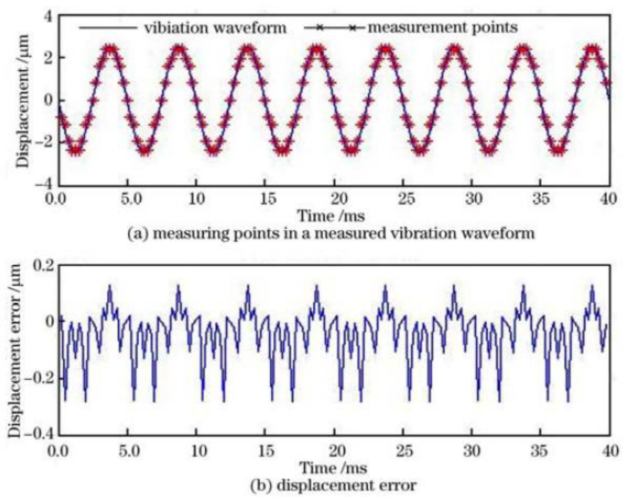

Figure 4. Error in displacement measurement: (a) distribution of discrete measurement points on the original vibration waveform; (b) error between the reconstructed vibration waveform and the original vibration waveform

Error in vibration measurement is mainly induced by the conflict between the frequency of the modulation current and the velocity of the target. The displacement of a target during one modulation period is given by $(\lambda/2)\Delta N$. Therefore, the minimum measurable displacement during each modulation period is $\lambda/2$, so the minimum measurable velocity can be written as $V_s = (\lambda/2)/T_s = (\lambda/2)f_s$, where f_s is the frequency of modulation current. While a target vibrates sinusoidally, the velocity of the target closest to the minimum measureable velocity appears at peak positions in a vibration. As a result, the maximum errors in measurement always appear at peak positions of a vibration.

3. EXPERIMENTAL RESULTS

By using of graphic tools of CCS software, the real-time reconstructed vibration waveforms are observed in Fig. 8. A loudspeaker is driven by a sinusoidal signal with 300 mV peak-to-peak amplitude at the frequency of 400 Hz. The peak-to-peak amplitude of three triangular modulation signals are with 300 mV, 400 mV and 500 mV at the same frequency of 4 kHz. The reconstructed vibration waveforms are shown in Fig. 5.

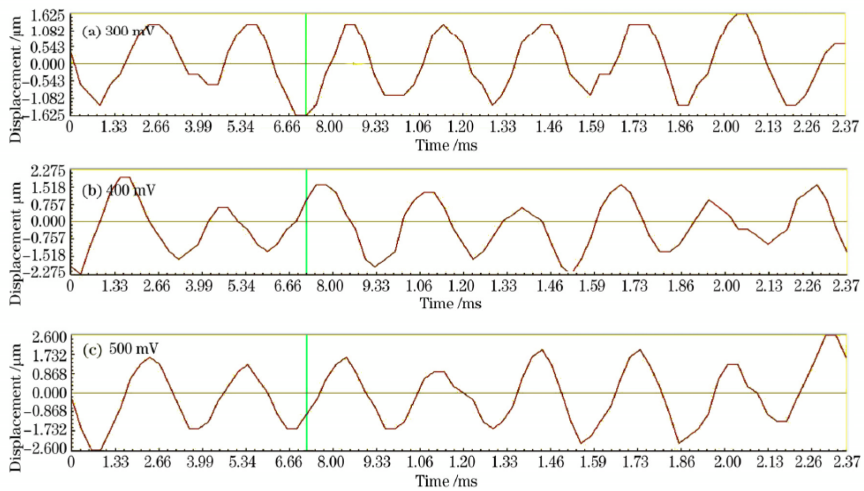

Figure 5. Measurement results observed by graphic tools of CCS at different peak-to-peak modulation signal: (a)300 mV, (b)400 mV, (c)500 mV.

As is shown in Fig. 5, the reconstructed vibration waveform agrees well with the applied signal to the loudspeaker. The frequency of the modulation current is 10 times as high as the frequency of the vibration, so we get 10 measurement points in one vibration period. The higher the frequency of the modulation signal is, the smoother the reconstructed vibration waveform becomes theoretically. However, the higher frequency of modulation signal leads to the an increase of minimum measurable velocity and distortion of the reconstructed vibration waveform at peak positions. So the suggested frequency of modulation current is 10 times as high as the frequency of vibration.

4. CONCLUSION

We have presented a new vibrometer which employs a self-mixing interference diode modulated by triangular injection current. The principle of vibration measurement is based on time integration of each sampled displacement which is measured during every period of the triangular modulation signal. The accuracy of displacement measurement is 0.325 micron. Since we have chosen DSP as core processing unit of this system, the vibrometer, which is very compact and inexpensive, meets the needs of real-time vibration measurement with high accuracy. This vibrometer is suitable for commercial use with improvement in miniaturization, intelligence and portability.

ACKNOWLEDGMENTS

This work was supported by the Specialized Research Fund for the Doctoral Program of Higher Education and Jiangsu Province High-novel Technology Project, and by the Natural Science Foundation of Jiangsu Higher Education Institutions of China , No 08KJB510008.

REFERENCES

[1] G. Giuliani, M. Norgia, S. Donati and T. Bosch, “Laser diode self-mixing technique for sensing applications,” Opt. A: Pure Appl. Opt. 4, 283-294 (2002).

[2] Ming Wang and Guanming Lai, “A self-mixing interferometer using an external dual cavity,” Meas. Sci. Technol. 14, 1025-1031 (2003).

[3] M. Norgia, S. Donati and D. D’Alessandro, “Interferometric Measurement of Displacement on a Diffusing Target by a Speckle Tracking Technique,” IEEE Journal of Quantum Electronics. 37(6), 800-806 (2001).

[4] G. Giuliani, Simone Bozzi-Pietra and S. Donati, “Self-mixing Laser Diode Vibrometer,” Meas. Sci. Technol. 14, 24-32 (2003).

[5] S. Shinohara, A. Mochizuki, H. Yoshida, and M. Sumi, “Laser Doppler velocimeter using the self-mixing effect of a semiconductor laser diode,” Appl. Opt. 25(9), 1417-1419 (1986).

[6] T. Suzuki, S. Hirabayshi, O. Sasaki and T. Maruyama , “Self-mixing Type of Phase-locked Laser Diode Interferometer,” Opt. Eng. 38(3), 543-548 (1999).

[7] M. Norgia and S. Donati, “A Displacement-measuring Instrument Utilizing Self-mixing Interferometry,” IEEE Transactions on Instrumentation and Measurement, 52(6), 1765-1770 (2003).