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Measurement module based on a common-path Fabry-Pérot interferometer for determining three-degree-of-freedom motion parameters

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Abstract
In this investigation, a novel three-degree-of-freedom laser interferometer is proposed which enables to determine the motion parameters including linear displacement, horizontal and vertical straightness in a linear axis. The modified common-path Fabry-Pérot interferometer consists of two optical arrangements for measuring the linear displacement and the straightness respectively. In the optical arrangement of the linear displacement measurement, the one eighth waveplate in the Fabry-Pérot optical cavity constructed with a planar mirror and a corner cube retro-reflector (CCR) is employed to form the orthogonal phase shift between interferometric signals and then they can be acquired by two photodiodes (PDs) to detect the linear displacement. In the other optical arrangement, a quadrant photodetector (QD) serves to inspect the lateral displacements induced by the dynamic offset of CCR. Furthermore, the relevant measuring characteristics of the self-developed laser interferometer are compact optical arrangement, convenient operation and efficient inspection. It would be beneficial for the linear positioning measurement and calibration of precision machines, e.g., linear positioning stages or high precision machine tools.

three- degree-of-freedom, linear displacement, straightness, linear stage

1. Introduction

In the precision mechanical industry, the manufacturing quality will be influenced directly by the precision of the motion stage. Hence, interferometric measurement or calibration technology is essential for the development of the precision engineering.

Due to the proposed investigations, the conventional Michelson laser interferometers are sensitive to the environmental disturbances and mechanical vibrations. Therefore, the critical point of the construction of an laser interferometer system is not only involved with the resolution and the corresponding measuring range, but also with the resistances of the environmental disturbances including thermal expansion and mechanical vibration [1]. Consequently, from the summarization of the above-mentioned descriptions, the self-developed system is based on the common-path structure being less sensitive to environmental disturbances. The proposed innovative multi-degree-of-freedom laser interferometer enables to determine the motion parameters including linear displacement, horizontal and vertical straightness in a linear axis. Therefore, a suitable measurement equipment for the dynamic displacement measurement and the calibration of the precision machine tools can be offered.

2. Optical arrangement

The main goal of the study is to establish an interferometer system which consists of a fixed and a moving component. With regard to the measurement requirements, there are two modules with different optical arrangements integrated in this system, including the linear displacement and the straightness module respectively [2-5]. The proposed interferometer has a stabilized He-Ne Laser source with high frequency stability and the wavelength of about 632.8 nm. And only a CCR is utilized in the moving component in order to form the Fabry-Pérot optical cavity for determining the displacement and to sense the straightness error. The integration of two measurement modules is illustrated in Fig. 1.

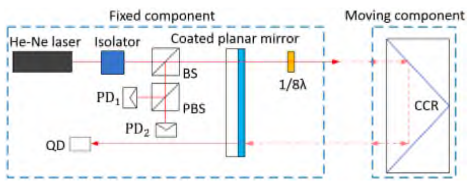

Figure 1. Three-degree-of-freedom laser interferometer

2.1. Linear displacement

From the Fig. 1, the folded Fabry-Pérot optical cavity is composed of planar mirror and CCR. Laser beam passes through the BS into the optical cavity. The one-eighth waveplate enables to realize the orthogonal phase shift between interferometric signals. The backward interferometric beams from the cavity will be divided by PBS whose the polarization axis must be identical to the waveplate and the orthogonal signals can be acquired by PDs. The optomechanical structure of the sensor head is shown in Fig. 2 and the complete volume is less than 126 × 100 × 245 mm^3. The compact sensor head will be desirable to reduce the thermal expansion error during long-term measurement.

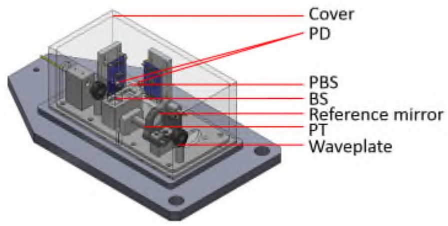

Figure 2. Structure of the sensor head

2.2. Straightness

In the Fig. 1, the QD serves to determine the deviations of the laser beam in two directions. The experimental structure for the verification of the straightness deviation is shown in Fig. 3. A CCR is installed at the linear stage with the resolution of 0.1 µm. The lateral displacements of X direction of the linear stage are equivalent to the changes of the straightness deviation.

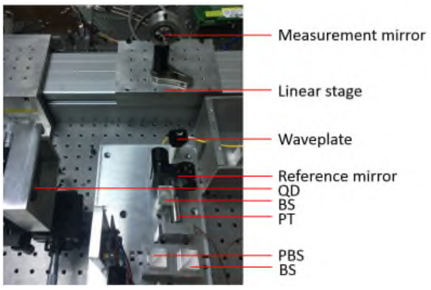

Figure 3. The experimental setup of straightness deviation

3. Experimental results

3.1. Linear displacement

The performance of the measuring range is tested in the precision linear stage. In the experimental testing, six measuring values are acquired by repeating measurements at the initial and final positions. According to these results listed in table 1, the displacement measurement is feasible in the measuring range of 500 mm.

Table 1 Testing results of measuring range

Linear displacement module		(Unit: µm)
Ideal position	Measured position	Deviation
0	-0.132	-0.132
500000	499991.250	-8.75
0	1.043	1.043
500000	499991.687	-8.313
0	-0.030	-0.03
500000	499991.437	-8.563

3.2. Primal sensing verification of straightness deviation

To verify the measurement feasibility of the interferometric beam, the relevant experimental testing of the straightness are demonstrated. The whole stroke of the linear stage is divided into eleven measuring intervals and each cycle is repeated five times. With the step interval of 10 µm, the position is altered from -50 µm to 50 µm and at each position 100 data will be acquired and then averaged. Further, voltage ratio versus the position (V-P curve) of the five measuring cycles are averaged, and then an averaged V-P curve can be obtained. Experimental results of different optical cavity lengths (210 and 274 mm) are presented in Fig. 4. The measurement results reveal the interferometric beam can be utilized for the measurement of the straightness.

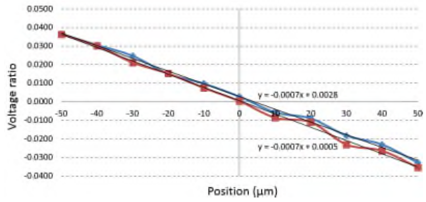

Figure 4. Experimental results of different V-P curves

3.3. Uncertaint Evaluation

By the JCGM100, the uncertainty of the system can be analyzed with two parts. One is wavelength error and the other is geometric error. Uncertainty evaluations are presented in table 2, where U_{LW} is the uncertainty of Laser wavelength, U_{WC} is the uncertainty of wavelength compensation, U_{Abbe} is the uncertainty of Abbe error and U_{cos} is the uncertainty of cosine error. At the assuming situation, the uncertainty of the system is about ± 222.4 nm.

Table 2 Uncertainty evaluation

Item / Error type		Evaluation parementer	Value	Total uncertainty
U_W	U_{LW}	Δλ	2 x 10^{-8} x λ	U = ± 222.4 nm
		U_{LW}	± 1.2 nm	
	U_{WC}	ΔT	± 0.2°C	
		ΔP	± 2 mm Hg	
		ΔH	± 20%	
		U_T	± 0.2 ppm	
		U_P	± 0.8 ppm	
		U_H	± 0.25 ppm	
		U_{WC}	± 49.8 nm	
U_G	U_{Abbe}	h	15 mm	
		θ_{Abbe}	5”	
		U_{Abbe}	± 209.9 nm	
	U_{cos}	θ_{cos}	5”	
		U_{cos}	± 54.1 nm	

4. Conclusion and future work

In this study, a flexible and innovative optical arrangement of three-degree-of-freedom Fabry-Pérot interferometer has been proposed. It can be summarized that the designed linear displacement module is available in the measuring range of 500 mm and the transmitted interferometric beam can be employed to the straightness measurement. In the future work, the theoretical error separation of straightness will be analyzed in detail including three dimensional matrix transformation and ray tracing of CCR. By the optimization of the optical structure, the motion parameters of the linear displacement and straightness errors can be measured simultaneously.

5. Acknowledgments

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