A New Method to Extend the Measurement Range of a Displacement Measuring Interferometer by Measuring the Modulation Depth

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Abstract Laser interferometers are widely used for sub-micrometer accuracy of measurements. However, conventional interferometers (homodyne and heterodyne interferometers) can be used to measure the displacement only. Therefore, the measurement signal must be continuous during the measurement process. This is difficult for a long measurement range with the presence of vibrations, misalignment of the optics, and tolerance of sliders. In this paper, a method of retrieving the absolute distance of the measured object by determining the modulation depth was proposed and demonstrated. This was the unique feature of the frequency-modulated interferometer. The modulation index is a function of the modulation excursion, modulation frequency, and the unbalanced length between the two arms of the interferometer. On the other hand, the modulation index can be determined through the Bessel function. Therefore, the absolute position of the target at special values of the modulation depth can be determined. These positions were utilized as markers on the scale to divide a large measuring range into small measuring ranges while ensuring the continuity of the system. Therefore, the proposed method can extend the measuring range of the interferometer even under the influence of vibrations or misalignment systems.

Keywords Modulation depth · Laser interferometer · Displacement measurement · Frequency modulated interferometer

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1 Introduction

Nowadays, ultra-precision machining plays a significant role that belongs with new machining technologies, especially CNC machining centers still account for a considerable proportion of modern machining methods. Therefore, the accuracy of mechanical machining is improved by using CNC machining centers which is always a key direction with many innovative research problems have been conducted [1, 2]. Machining accuracy is fully controlled by drive systems and standard linear translation stages. The accuracy of the standard stage depends on the driven system including shape deviation (straightness, flatness), relative position deviation (parallelism, perpendicularity), and the accuracy of displacement [3, 4]. In working conditions, shear force, friction, and temperature deform material reduce the accuracy of the linear guided stage, so the standard guided stage must be carefully inspected and calibrated. The challenge from the standard measurement system of machining centers or machine tools highly requires accuracy in an enormous range of measurements, under the influence of vibrations from the measuring environment, and a large measuring speed. The precision of mechanical machining is increasing rapidly which makes huge challenges and motivates the field of measurement and calibration. Research articles in this field are diverse, new displacement encoders can achieve the nano-level of accuracy and are less dependent on environmental changes (temperature, refractive index) [5–7]. However, the disadvantage of an encoder that the measuring range is always smaller than the encoder geometrical size. The larger encoder is the more difficult it makes when integrated into a mechanical machining system. In contrast, capacitive sensors are often used in the small displacement range [8–10]. A capacitive sensor has a high resolution, 1 nm/1 μm in measuring range, but the measuring range is small ($< \pm 3$ mm) and does not suitable for large displacement systems of machine tools, and machining centers. The two-frequency interferometer can achieve 1 nm resolution in an extensive range of measurements [11–15]. The limitation due to this method that system is quite large, is difficult to install in a machining system, and is sensitive to noise and expensive. Currently, we developed a frequency-modulated semiconductor laser to overcome the above disadvantages [16–18].

In this study, the laser diode allows frequency modulation through direct injection current modulation. In the evaluated system, the standard linear stage was calibrated carefully using a laser interferometer. The modulation amplitude was actively controlled so that achieving the high quality of component harmonic signal in different measuring ranges, the influence of vibration and the change from the environmental refractive index was eliminated by the flexible frequency filter. The measurement speed of the system was enhanced by using a higher modulation frequency for the semiconductor laser by modulating the direct injection current of the laser diode. The new idea from this research is the ability to retrieve the absolute distance of the measured object. Therefore, the measurement signal must be continuous and interrupted free. This is difficult to complete in working conditions of machining centers which require a large displacement range, strong vibrations, and misalignment of the linear guided stage in the drive system, which easily leads to loss of interference signals. In the frequency modulated interferometer, the modulation index is a function of modulated amplitude, modulated frequency, and the difference between the two arms of the interferometer. In addition, the modulation index can be determined by using the Bessel function. In this study, the method of determining the absolute position of measuring objects at critical values of modulation depth was proposed. These known positions function as marker points on the scale. These points were used to divide the large measuring range into small measuring ranges while ensuring the continuity of the measuring system. Therefore, this method can solve important problems such as extending the measuring range of the interferometer even under the influence of vibrations or misalignment from the drive system. In addition, by improving the measuring speed of frequency modulated interferometer so that it can be applied to measure during the machining process and is also an achievement of this study. Furthermore, the proposed interferometer can operate stably in noisy environments like factories and manufacturing plants, under the impact of vibrations and the change of environment refraction index.

2 Measurement Principle

The intensity $I(\tau, t)$ of the interference signal of the frequency modulated interferometer is written as [16–18]

$$\begin{aligned} I(\tau, t) = E_{01}^2 + E_{02}^2 &+ 2E_{01}E_{02}\cos(\omega_0\tau)J_0(m) \\ &+ 4E_{01}E_{02}\cos(\omega_0\tau)\sum_{n=1}^{\infty} J_{2n}(m)\cos(2n\omega t) \\ &- 4E_{01}E_{02}\sin(\omega_0\tau)\sum_{n=1}^{\infty} J_{2n-1}(m)\cos[(2n-1)\omega t], \end{aligned} \tag{1}$$

where τ, m, E_{01} and E_{02}, n, $J_0(m)$, $J_{2n}(m)$, and $J_{2n-1}(m)$ are the changes in time between the two arms of the interferometer, the modulation index, the amplitudes of the electric fields in the reference and measurement arms, an integer, and the Bessel functions, respectively. Here,

$$m = \frac{\Delta\omega}{\omega}\sin\left(\frac{\omega\tau}{2}\right) \approx \frac{2\pi\Delta f n_{\mathrm{air}} L}{c} \tag{2}$$

where Δf ($\Delta\omega = 2\pi\Delta f$), n_{air}, L, and c are the frequency modulation excursion, the refractive index of air, the unbalance length of the interferometer, and the light velocity in a vacuum. A divider split $I(\tau, t)$ into two parts, which are coupled into the two purely sinusoidal signals of 2ω and 3ω from the function generator. By using the two LIAs, the intensities $I_{2\omega}$ and $I_{3\omega}$ of the 2ω and 3ω harmonics of $I(\tau, t)$, respectively, are produced as follows

$$\begin{aligned} I_{2\omega} &= 2E_{01}E_{02}\cos(\omega_0\tau)J_2(m), \\ I_{3\omega} &= -2E_{01}E_{02}\sin(\omega_0\tau)J_3(m). \end{aligned} \tag{3}$$

Here, $J_2(m)$ and $J_3(m)$ are the second and third order Bessel functions. By using the Lissajous diagram, $\omega_0\tau$ is determined. The total phase difference Φ between the arms is

$$\Phi = \omega_0\tau = \arctan\left(-\frac{I_{3\omega}}{I_{2\omega}}\cdot\frac{J_2(m)}{J_3(m)}\right). \tag{4}$$

The displacement ΔL calculated from the phase shift is given by

$$\Delta L = \frac{\lambda_0}{4\pi n}\arctan\left(-\frac{I_{3\omega}}{I_{2\omega}}\cdot\frac{J_2(m)}{J_3(m)}\right). \tag{5}$$

Figure 1 shows the Bessel functions from $J_2(m)$ to $J_4(m)$. There are some critical points where two consecutive Bessel functions are equal, $J_1(m) = J_2(m)$ when $m =$ 2.63 rad and $J_2(m) = J_3(m)$ when $m = 3.77$ rad. The displacement ΔL is independent on the modulation index m at various specific value of m, hence Eq. (5) become

$$\Delta L = \frac{\lambda_0}{4\pi n}\arctan\left(-\frac{I_{3\omega}}{I_{2\omega}}\right). \tag{6}$$

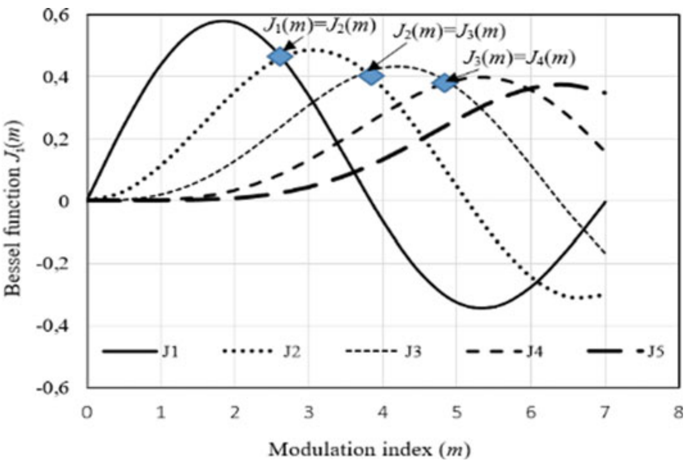

Fig. 1 Bessel function

The measurement uncertainties of modulation index measurement and approximation Bessel function value are removed from uncertainty sources of the proposed interferometer.

In this paper, the modulation index was carefully controlled to reach some special values (2, 63, 3.77…). The modulation index depends on the unbalanced length, and modulation excursion as shown in Eq. (2). Laser diodes offer modulation frequency directly by modulating the injection current. Therefore, the modulation excursion is adjusted to obtain the special values of the modulation index. At the values, the Lissajous diagram generated from two consecutive harmonics is circular. Moreover, Eq. (2) proves that when the modulation excursion Δf and the modulation m are known, the unbalanced length L can be determined. It means that the absolute position of the measuring object at critical values of the modulation depth can be determined immediately. These known positions function as markers on the scale and critical points are used to divide the large measuring range into small measuring ranges while ensuring the continuity of the system. This method is immensely helpful to extend the measuring range of the frequency modulated interferometer and limit the effects of vibrations or straightness errors that can lose interference signal during the broad range of measuring displacements.

3 Experiment and Discussion

The experiment was designed to verify two characteristics of the proposed method, the controlling of modulation index by adjusting the modulation excursion and the displacement measurement at a critical value of modulation index. The experimental system is shown in Fig. 2. A collimated laser diode (HL6344G, Thorlabs Inc.) at the wavelength of 633 nm was used as a light source for the interferometer. The movement of the reference mirror was sinusoidally modulated by a PZT actuator (PA4FKW, Thorlabs Inc.). The interference signal was detected using a photodetector (PDA36A-EC, Thorlabs Inc.). A signal processing module was built by combining analog lock-in amplifiers and high-resolution data acquisition. The experimental condition was shown in Table 1.

The modulation excursion was adjusted by changing the amplitude of modulation current. When the modulation excursion was equal to 360 MHz the modulation index obtained 2.67. The Lissajour diagram was circle and the displacement measured was independent to the modulation index. The displacement was successfully measured with low noise, Fig. 3. Moreover, the absolute length of 3.489 m can be determined when $m = 2.63$.

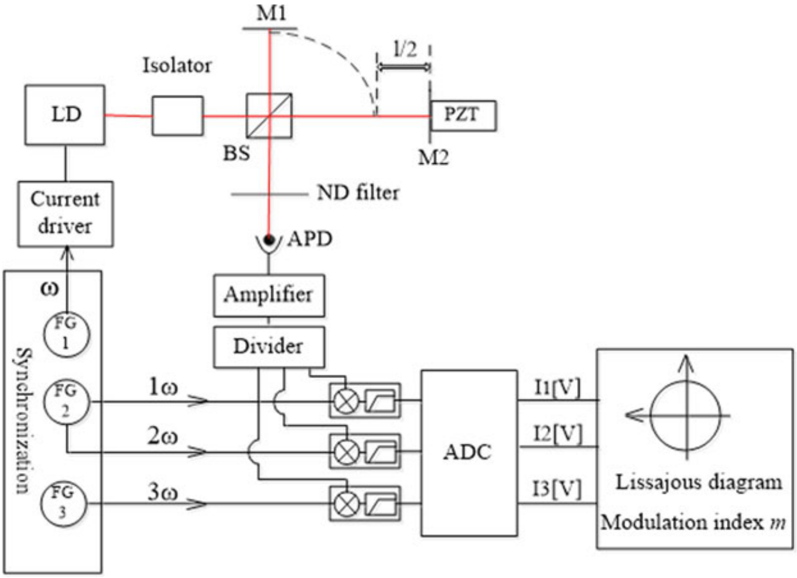

Fig. 2 Experimental setup for frequency modulated interferometer

Table 1 The experimental conditions

Frequency modulation for LD	3 MHz
Frequency modulation excursion for LD	360 MHz
Operating frequency of PZT	1 Hz
Amplitude of PZT stage	0.5 µm (0.5 Vpp)
Wavelength	633 nm
Cut off frequency of low pass filter	1 MHz

4 Conclusion

This research was proposed and verified a new method to extend the measurement range of a frequency modulated interferometer. The modulation index was controlled to reach some special values, where two consecutive harmonics have the same Bessel function value. The displacement was measured without any effect of the modulation index. Moreover, the absolute value of length can be determined at the critical value of the modulation index.

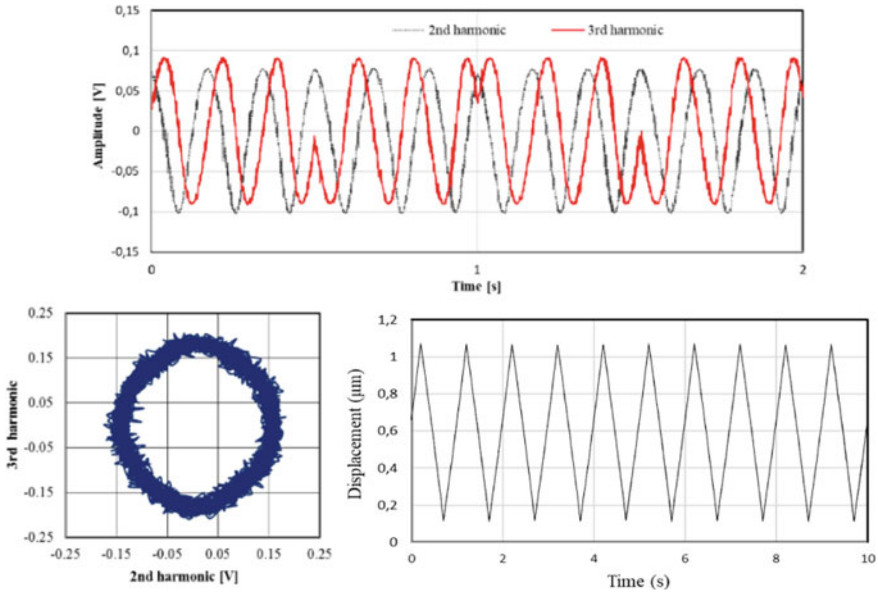

Fig. 3 Lissajous diagram and displacement measurement result

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