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Ultra-precision alignment technique based on modified Moiré signals

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Abstract: A novel method for automatic ultra-precision alignment is presented. This method relies on the modified Moiré technique, and alignment marks are used in the form of gratings. The modified Moiré technique can effectively improve detecting sensitivity of signals and simplify the control system by using only one pair of laser-Moiré sensors. We present the mathematical model and simulation results of diffracting two gratings. The effect of various parameters on Moiré signals is studied theoretically and experimentally, and the results are found to be consistent. A computer controlled alignment device using one pair of Moiré sensors is designed. The device can achieve a fully automatic precision alignment by the modified Moiré signal. The experimental result shows that the alignment device can obtain the resolution of 5 nm and the positioning accuracy of ±0.5 μm.

Key words: Moiré signal; ultra-precision alignment; modified Moiré technique; automatic control

Ultra-precision alignment technology has become one of the most attractive research fields in recent years. The technology is widely pursued by industries of ultra-precision manufacturing, VLSI fabrication, electronic product assembly, biological engineering and nanometer technology. Several alignment methods have been developed, but the expected accuracy can only be achieved with the help of highly accurate and sensitive optical methods. The Moiré technique is one such optical method that has been considered for ultra-precision alignment[1-6]. Some experiments with alignment accuracy at ±4 nm in linear direction have been reported in some countries.

A novel technique for automatic alignment is proposed in this paper. We use a computer-aided control system with one pair of laser-Moiré sensors to send out the 0-th order modified Moiré signal as a control signal to achieve the automatic alignment at high accuracy of sub-micron.

1 Principle of Precision Alignment

1.1 Laser-Moiré sensors

Fig. 1 shows the components forming a single laser-Moiré sensor. Two gratings are placed parallel to each other. When the laser beams pass perpendicularly through the pair of gratings, they are diffracted by the gratings, and transmission Moiré signals are obtained. The intensity $\Psi_t(\Delta x, G)$ of the 0-th order Moiré signals changes periodically corresponding to the position shift of the two gratings. The relations are given as follows[7-9]:

$$\Psi_t(\Delta x, G)_0 = A_t \int_{-\frac{W_2}{2}}^{\frac{W_2}{2}} \Psi_1(x_1, G)\,\mathrm{d}x_1 \tag{1}$$

$$\Psi_1(x_1, G) = A_1 \sum_{l=-M/2}^{M/2} \int_{-\frac{W_1}{2}}^{\frac{W_1}{2}} r^{-\frac{1}{2}} \left(1 + \frac{G}{r}\right) \exp(-\mathrm{i}kr)\,\mathrm{d}x_0 \tag{2}$$

$$r = [G^2 + (x_0 - x_1 + lP)^2]^{\frac{1}{2}} \tag{3}$$

where $k = 2\pi/\lambda$, λ is the wavelength of the light used; P is the grating constant; G is the space between the gratings; M is the number of slits in the grating; W_1 is the width of each slit in the first grating; W_2 is the width of each slit in the second grating; and Δx is the relative displacement between two gratings.

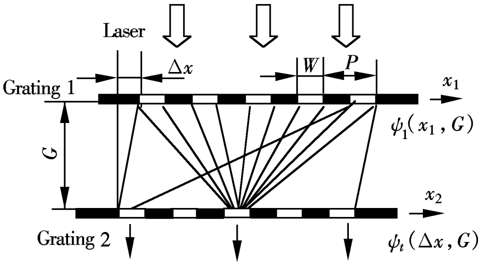

Fig. 1 Arrangement of gratings

The calculated displacement characteristics of transmission 0-th order Moiré signal are shown in Fig. 2(a). The intensity of signals varies periodically

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within the Fresnel zone with relative displacement of the gratings, and with the space between the two gratings. The maximum intensity is obtained at the condition of $G = nP^2/\lambda$, where n is an integer.

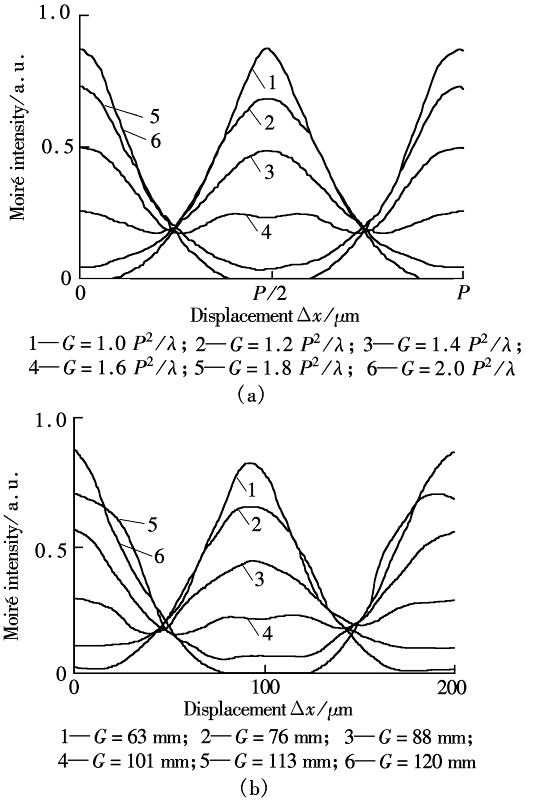

Fig. 2 Displacement characteristic of the 0-th order Moiré signals. (a) Calculated Moiré signal; (b) Measured Moiré signal

The experimental results are shown in Fig. 2(b). A He-Ne laser with the wavelength of 633 nm is used as a light source. The experimental results correspond nicely with the theoretical computing results.

Based on the relations presented above, the precision position can be achieved by converting the 0-th order Moiré signals into electronic signals through photodiode, and then detecting the displacement Δx by measuring the signals' intensity.

1.2 Modified precision alignment technique

In order to improve the alignment accuracy, the precision control system is modified. This system uses one pair of laser Moiré sensors, which is simpler than the differential Moiré system[9-11]. The maximum, minimum and instantaneous values of the Moiré signal intensity are examined. The inverted version of the Moiré signal is calculated by the following equation:

$$I_0 = I_{1\max} + I_{1\min} - I_1 \quad (4)$$

where I_1, $I_{1\max}$, $I_{1\min}$, and I_0 are the instantaneous value, maximum, minimum and inverted version of the Moiré signal, respectively. The difference of I_1 and I_0, which is used as a control, is calculated as follows:

$$S_m = I_1 - I_0 = 2I_1 - (I_{\max} + I_{\min}) \quad (5)$$

The detected intensities of Moiré signals I_1, inverted Moiré signals I_0 and modified Moiré signals S_m are shown in Fig. 3. We can draw three findings: ① Modified technique doubles position displacement Moiré signals; ② The gradient of modified signal intensity change becomes much sharper at the alignment point, which means that a tiny displacement can cause dramatic intensity change in that area so that the signal detection sensitivity can be improved at the alignment point; ③ There is a linear relationship between intensity and granting displacement at the alignment point so that it is possible to quantify the value of the displacement and to judge its orientation.

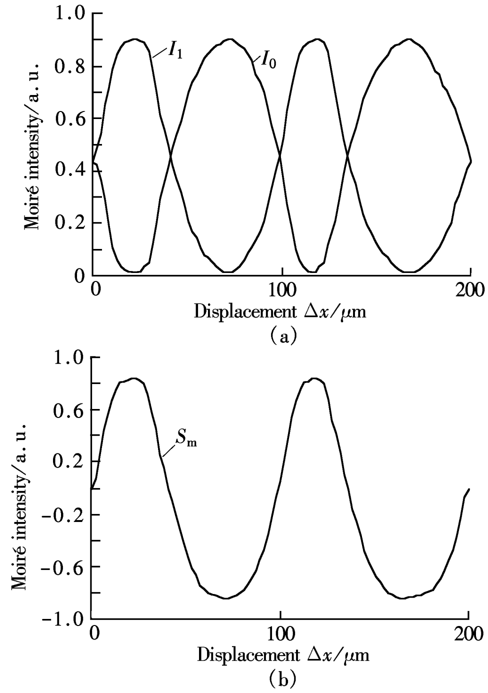

Fig. 3 Modified Moiré signal system. (a) Detected Moiré signal and inverted Moiré signal; (b) Modified Moiré signal

The intensity of the modified Moiré signal changes periodically with the relative displacement of the two gratings. In one cycle, the point at which the modified signal intensity is zero is treated as an alignment point; the precision alignment range is from $-P/2$ to $+P/2$ of the alignment point.

2 Apparatus of Precision Alignment

Fig. 4 shows the schematic diagram of the apparatus of the precision alignment. The laser generates one bundle of laser beams; this bundle is sent through a set of spectroscopes and gets separated into two bundles of laser beams. Then the beams perpendicularly pass though a pair of gratings, which diffracts transmission 0-th order Moiré signals. These Moiré signals received by two photodiodes are then amplified and filtered to reduce the noises presented in the amplifier

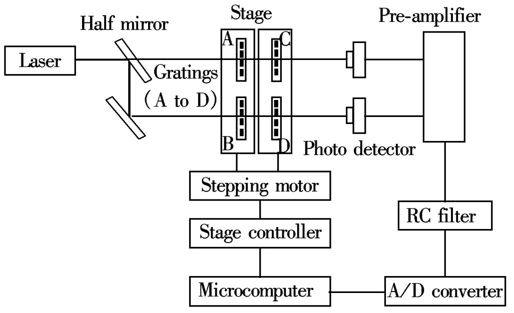

Fig. 4 Apparatus of precise alignment

outputs. The signals are converted into digital signals by A/D converters. The converted signals are transferred to the computer.

2.1 Photo-electrical detecting circuits

The photodiode receives the 0-th order Moiré signals diffracted by the gratings, and transforms them into electrical signals that always are at μA-level. Because our control computer only works with 0 to 10 V voltage signals, we have to pretreat input signals. Fig. 5 shows the pretreating circuits. Amplifier IC_1 acts as the first stage current-voltage transforming circuit and the converted voltage is

$$U_1 = I_0 R_2 \tag{6}$$

where I_0 is the current from photodiode, and resistance $R_2 = 20$ kΩ.

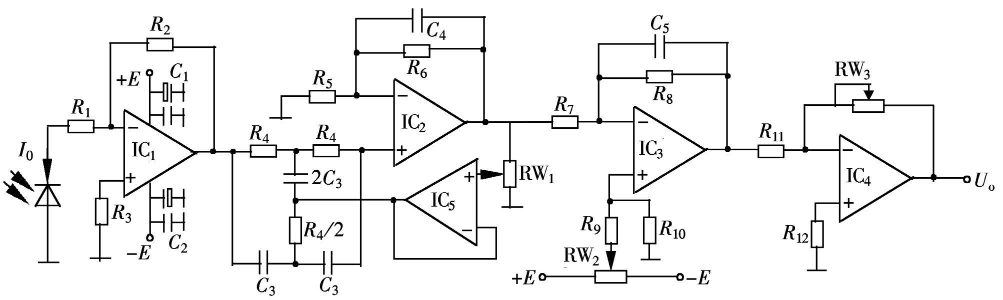

Fig. 5 Photo-electrical detecting circuits

Because the detected signals are so weak that they are likely to introduce noise when being amplified, graded amplifiers and filters are considered to avoid the flaw of the signals and noise being amplified at the same time. T-form low-pass filter is also added to the circuit to eliminate 50 Hz noise. We adopt a three-grade amplifier, composed of sub-amplifiers IC_2, IC_3 and IC_4. Its magnification is

$$K = \frac{R_9 R_{11} RW_2}{R_8 R_{10} R_{14}} \tag{7}$$

where $R_8 = 10$ kΩ, $R_9 = 100$ kΩ, $R_{10} = 1$ kΩ, $R_{11} = 100$ kΩ, $R_{14} = 10$ kΩ, $RW_2 = 100$ kΩ (adjustable precision resistance).

Additionally, we apply a zero-drift compensation circuit to eliminate dark-current from the photodiode and zero-shift of amplifier.

2.2 Controller and mechanical drive system

We design two-grade positioning in our system: preparatory positioning and precise positioning. First, preparatory alignment is achieved via a preparatory platform from which we get the alignment position with an accuracy of $\pm P/2$ in horizontal and vertical. And then, precise alignment is processed via controlling the precise platform. This strategy can shorten positioning time, and at the same time achieve precise alignment. The preparatory platform can move freely along a 3-dimensional (x, y, z) plane via precise screw driver set; the mechanical drive system of the precision platform is composed of a stepping servomotor in micro step mode and high precision Archimedes helix cam, which can translate small rotational movement into sub-micron level linear movement. The final alignment error is mainly eliminated through a computer-controlled closed loop so as to alienate the precision requirements of the mechanical drive system.

When proceeding to precise alignment, the industry control computer will automatically manage the precise platform and put it into the expected position based on the Moiré signal and its orientation.

3 Experiment of Precision Alignment

Light source of the experiment is a He-Ne laser with a power of 1.8 mW and a wavelength of 633 nm. The grating constant $P = 100$ μm. The distance between two gratings is 1 mm. The minimum pulse moving distance after 10^4 times subdivision is 0.2 μm. An industry control computer is used to automatically send out enacted pulses to move the precise platform into the expected position. And even if the system gets out of the correct position by disturbance or vibration, it will correct itself to the expected position. The curve of alignment is shown in Fig. 6. The two broken lines show the upper and lower predetermined reference values. The reference values are within ±0.5 μm. The positioning accuracy is ±0.5 μm in our experiment.

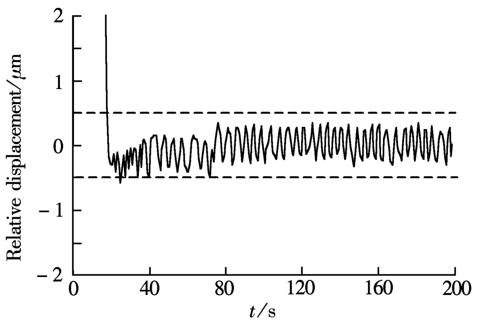

Fig. 6 Accuracy of precise alignment

4 Conclusion

In this paper, we present a mathematical model and the simulation results of diffracting two gratings based on the model. Then we propose a novel technique of high precision alignment based on a modified Moiré signal. This method can improve the sensitivity of signal detection via only one pair grating, so the apparatus is also simple. The experimental results show that our alignment apparatus based on the modified Moiré signal can effectively improve positioning accuracy, and achieve an accuracy of approximately ±0.5 μm.

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基于修正莫尔信号的超精密定位技术

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摘要: 提出了一种新的超精密定位方法, 该方法基于修正莫尔技术, 以衍射光栅作为定位标记, 可有效提高位置检测信号的灵敏度, 且结构简单. 建立了双光栅位移测量的数学模型, 并进行了计算机仿真, 用实验验证了激光莫尔信号特性的理论计算结果与实验测定结果的一致性. 在此基础上, 构建了一套以工业控制计算机为核心的精密定位装置, 以修正莫尔信号为控制信号, 由微机控制实现精密自动定位. 系统通过软硬件方面的一系列抗干扰措施, 确保了定位的高精度. 实验结果表明基于修正莫尔信号的全自动精密定位装置可获得 5 nm 的位移分辨率及 ±0.5 μm 的定位精度.

关键词: 莫尔信号; 超精密定位; 修正莫尔技术; 自动控制

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