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Ultra-precision positioning control technique based on neural network

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Abstract: Due to the non-linearity behavior of the precision positioning system, an accurate mathematical control model is difficult to set up, a novel control method for ultra-precision alignment is presented. This method relies on neural network and alignment marks that are in the form of 100 μm pitch gratings. The 0-th order Moiré signals' intensity and its intensity rate are chosen as input variables of the neural network. The characteristics of the neural network make it possible to perform self-training and self-adjusting so as to achieve automatic precision alignment. A neural network model for precision positioning is set up. The model is composed of three neural layers, i. e. input layer, hidden layer and output layer. Driving signal is obtained by mapping Moiré signals' intensity and its intensity rate. The experimental results show that neural network control for precision positioning can effectively improve positioning speed with high accuracy. It has the advantages of fast, stable response and good robustness. The device based on neural network can achieve the positioning accuracy of ±0. 5 μm.

Key words: Moiré signals; ultra-precision alignment; neural network; intelligent control

Ultra-precision alignment technology has become one of the most attractive research fields in the world in recent years. The technology is widely pursued by industries of ultra-precision manufacture, VLSI fabrication, electronic product assembly, biological engineering and nanometer technology. Several automatic alignment methods based on the Moiré technique have been developed[1 - 7]. However, because of its complicated process and non-linearity expression, the positioning system is, with difficulty, controlled by an accurate mathematical control model; therefore, classical control theories can no longer make a breakthrough. The evolution of neural network has provided a novel approach for precise positioning. Artificial neural network (ANN) may approximate any non-linear functions, and have the ability of self-training, self-adjusting and is independent of the mathematical model. This paper presents an ANN approach for precision positioning control. The experimental results show that the system with a neural network control effectively improves positioning speed and positioning accuracy.

1 Principle of Precision Alignment

The principle of precision alignment is based on the Moiré interference technique. Fig. 1 shows the schematic diagram of gratings arrangement. When a laser beam is irradiated to striped diffraction gratings arranged in parallel, a diffraction Moiré signal is produced. The amplitude of the 0-th order Moiré signals diffracted from the first grating is calculated using the Fresnel diffraction integral, given by[8 - 10]

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

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

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

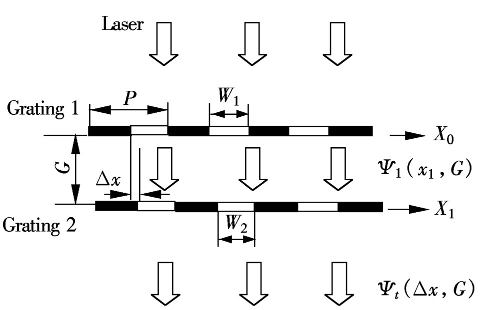

Fig. 1 Arrangement of gratings

The amplitude of the 0-th order Moiré signals diffracted from the second grating was calculated by using the Fraunhofer diffraction integral, given by[8 - 10]

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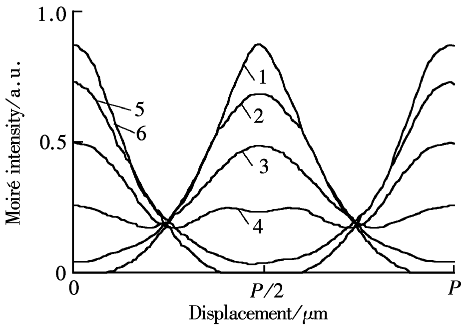
$$\Psi_t(\Delta x, G)_0 = A_t \int_{-\frac{W_2}{2}+\Delta x}^{\frac{W_2}{2}+\Delta x} \Psi_1(x_1, G)\,dx_1 \qquad (3)$$

The calculated displacement characteristics of the transmission 0-th order Moiré signal are shown in Fig. 2. The intensity of signals fluctuates periodically within the Fresnel zone with relative displacement of the gratings and with the space between the two gratings. The maximum intensity is obtained under the condition of $G = nP^2/\lambda$, where n is an integer.



1—$G = 1.0\ P^2/\lambda$; 2—$G = 1.2\ P^2/\lambda$; 3—$G = 1.4\ P^2/\lambda$; 4—$G = 1.6\ P^2/\lambda$; 5—$G = 1.8\ P^2/\lambda$; 6—$G = 2.0\ P^2/\lambda$

Fig. 2 Calculated results of the 0-th order Moiré signals

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

2 Neural Network Controller

The controlling process for precision positioning is very complicated. It is obviously not linear. Consequently, a precise mathematical control model is difficult to obtain. An artificial neural network can perform parallel processing and self-training, it can also construct relationships between input and output by learning from samples. We utilize the neural network as a precision positioning controller. The pulses y of step motor is calculated by the intensity x_1 of the 0-th order Moiré signals and its intensity rate x_2. The neural network used is a regular error back-propagation neural network (BP net). As shown in Fig. 3, the network contains three layers: the first layer is an input layer, containing two nodes corresponding to inputs of the intensity x_1 of the 0-th order Moiré signals and its intensity rate x_2, respectively; the second layer is a shielded layer, containing seven nodes; and the third layer has only one node, representing the driving pulses of the step motor. In the following section, h denotes the elements of the input layer, i denotes the shielded layer, and j denotes the output layer, the respective input and output are x_{kh} and d_{kj}. The transfer

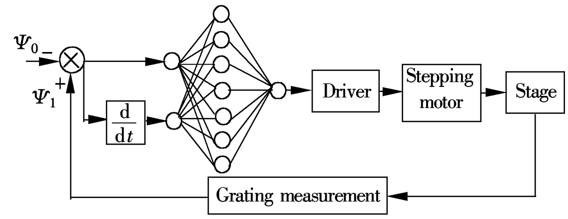


Fig. 3 Neural network model of precision alignment

function for each node in the network is expressed with the sigmoid function. Error function is represented with $E_k = \frac{1}{2}\sum(y_j - d_{kj})^2$. The output y_i from each node of the shielded layer is

$$x_i = \sum_{h=1}^{2} w_{hi} x_{kh} + \theta_i \qquad (4)$$

$$y_i = \frac{1}{1 + \exp(-x_i)} \qquad i = 1, 2, \ldots, 7 \qquad (5)$$

The output y_j from each node of the output layer is

$$x_j = \sum_{i=1}^{7} w_{ij} y_i + \theta_j \qquad (6)$$

$$y_j = \frac{1}{1 + \exp(-x_j)} \qquad j = 1 \qquad (7)$$

Right value and threshold value are modified by the following equations[11]:

$$\omega_{ij}(t+1) = \omega_{ij}(t) - \eta \frac{\partial E_k}{\partial x_j} y_i + \alpha[\omega_{ij}(t) - \omega_{ij}(t-1)] \qquad (8)$$

$$\theta_j(t+1) = \theta_j(t) - \eta \frac{\partial E_k}{\partial x_j} + \alpha[\theta_j(t) - \theta_j(t-1)] \qquad (9)$$

$$\omega_{hi}(t+1) = \omega_{hi}(t) - \eta \frac{\partial E_k}{\partial x_i} y_h + \alpha[\omega_{hi}(t) - \omega_{hi}(t-1)] \qquad (10)$$

$$\theta_i(t+1) = \theta_i(t) - \eta \frac{\partial E_k}{\partial x_i} + \alpha[\theta_i(t) - \theta_i(t-1)] \qquad (11)$$

where the momentum factor $\alpha \in (0, 1)$, and t is the modifying quantity.

A total of 30 sets of samples used to train the neural network were measured and collected from a precision positioning system shown in Fig. 4. The off-

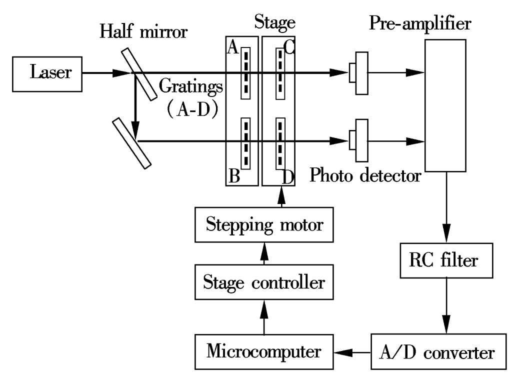


Fig. 4 Experimental apparatus of precision alignment

line trained neural network was later used as the real time controller of the positioning system.

3 Experimental Setup

The experimental setup for the alignment system is shown in Fig. 4. The laser beam is divided into two beams by a beam splitter and allowed to pass perpendicularly through the grating pairs. Two pairs of gratings with spatial phase differences of 180° are used. The 0-th order beams are detected by two photodiodes and amplified by the pre-amplifier. The signals are converted into digital signals by the A/D converter. The converted signals are transferred to a computer. The difference between the Moiré signals by the two grating pairs is calculated, and the stage is moved stepwise until the difference comes within predetermined reference values. If the stage gets out of the correct position by disturbance or vibration, it is again controlled automatically. A semiconductor laser (635 nm) is used as the laser beam. The pitch of the gratings is 100 μm, the gap between two gratings is 1. 0 mm. The stage is controlled by a stepping motor in micro step mode, and the one step is 0. 1 μm.

4 Result and Discussion

Three control methods, regular control, fuzzy control and neural network control, were tested for precision positioning. Respective derived curves are shown in Fig. 5. In regular control, the stage is moved stepwise until the difference comes within predetermined reference values. The initial position of the stage, shown in Fig. 5, is identical for the three methods. They are all 40. 5 mm. The predetermined reference value is ±0. 5 μm; i. e. , the positioning accuracy is ±0. 5 μm. Tab. 1 gives the positioning time of the three control methods, from which the ANN controller is shown to perform precision alignment in the shortest time of 16 s. This experiment also tested anti-noise ability by inputting identical noise sources. Fig. 5 shows that all the three controllers were strongly interfered with by noise; however, different control methods took different lengths of time to return to the desired position (see Tab. 1). The ANN controller took the shortest time for the transient period, namely 6. 5 s. Hence ANN has a higher ability of self-adjusting and anti-noise.

Tab. 1 Time for precision positioning

Control mode	Positioning time/s	Anti-noise transient period/s
Regular control	40	24
Fuzzy control	25	10
ANN control	16	6. 5

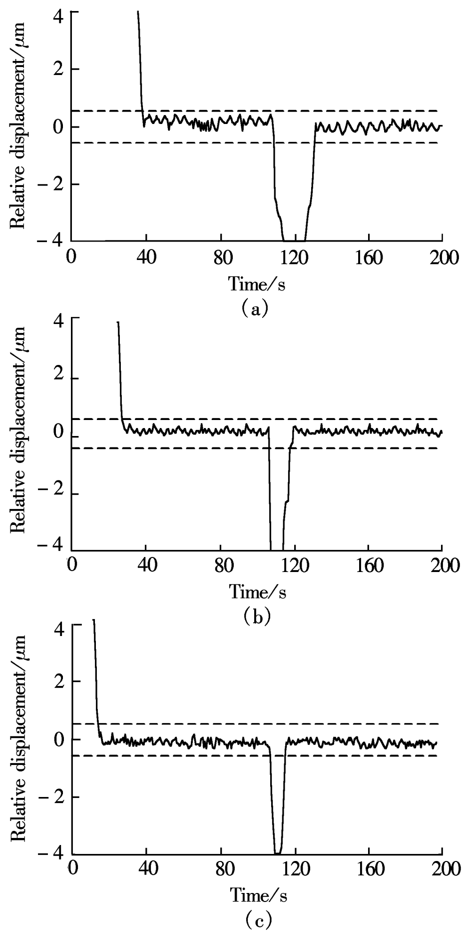


Fig. 5 Results of precision alignment. (a) Regular control; (b) Fuzzy control; (c) ANN control

5 Conclusion

The neural network control for precision positioning can effectively improve positioning speed with high accuracy. It has the advantages of fast, stable response and good robustness. The device based on the neural network can achieve the positioning accuracy of ±0. 5 μm. The approach is of high value for accelerating the advancement of precision manufacturing technology.

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基于神经网络的超精密定位控制

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摘要:针对精密定位装置存在非线性,精确数学模型难于建立的缺陷,提出了精密定位的神经网络控制方法.将BP神经网络应用于该控制系统中,系统以光栅常数100 μm的光栅为定位标记,以激光衍射产生的莫尔光光强及光强的变化率为神经网络的输入变量,利用神经网络的自学习功能进行精密定位控制.建立了精密定位的神经网络控制模型,模型由输入层、隐层和输出层3层神经元组成,通过对光强及光强变化率的映射,得到电机驱动信号.实验结果表明,使用神经网络控制,控制响应快,稳定性好,鲁棒性强,可有效改善控制质量,提高定位速度,系统可获得±0.5 μm的定位精度.

关键词:莫尔信号;超精密定位;神经网络;智能控制

中图分类号:TP274^{+}.5