Design and characteristics of piezoelectric actuator with single neuron adaptive PID controller for the grating tiling

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ABSTRACT

In this paper we propose a system with the piezoelectric actuator by the single neuron adaptive PID controller for the grating tiling. Then the design of the control system as well as the control method by considering the nonlinearity of piezoelectric actuators is discussed. At last, close loop position examinations by the capacitive displacement sensor with nanometer scale precision are performed. The experimental results indicate that the system is working effectively. The system is provided with the characters of self-learning, easy calculating and adaptability as well as of a simple structure.

Keywords: Grating tiling, Piezoelectric actuator, single neuron, adaptive PID control

1. INTRODUCTION

Multi-kilojoule Petawatt (PW) lasers using chirped pulse amplification (CPA) need large scale compression gratings. Since the difficult fabrication process for multilayer dielectric (MLD) diffraction gratings may limit the ultimate size of an individual grating to less than 1 meter, therefore, the grating tiling technology using some subaperture gratings to form a large-aperture high-damage threshold grating is a key approach to increase the output energy of the PW laser systems[1~2].

As shown in figure 1, there are five degrees of freedom (DOF) between the two adjacent gratings, namely, tip, tilt, rotation, in-plane shift dx and out-plane shift dz. For an example of coherent addition of segment gratings with the parameter of 1480l/mm in our experiment, the influence of the tiled grating on the laser beam in the temporal field should be less than 25%, and in the spatial field the influence on the wave front should be less than 1/10 wavelength.

According to the above requirements, we can calculate that the angular errors must be within 20μrad to ensure the precision of coplanarity about several tens of nanometers. The piston error must be limited to the range of 3~5 times of the wavelength of incidence, and the gap error should be less than 1/10 of groove width of the gratings[3~4]. So it is necessary for the mechanism and control system used in grating tilting it can provide with nanometer resolution precision and nanometer positioning stability.

Meanwhile, various types of modified PID controllers have been developed, such as self-tuning PID controllers[5] and fuzzy PID controllers[6] and so on. Among them, the self-tuning PID controller can provide a systematic and flexible approach to deal with uncertain, nonlinear and time varying parameters.

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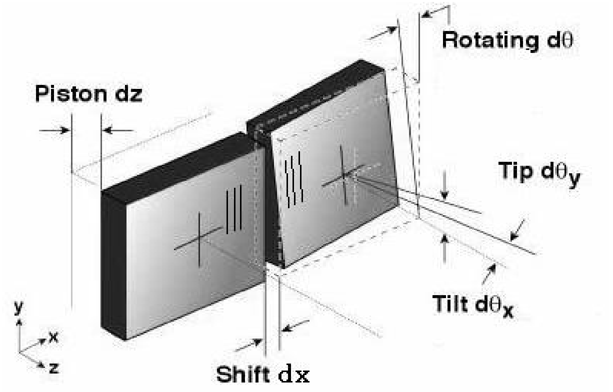

Fig. 1 five degrees of freedom between the two adjacent gratings

2. CHARACTERISTICS OF PIEZOELECTRIC ACTUATOR

To meet the requirement of grating tilting and obtain a resolution of nanometer scale, we adopted an ultra-precision stage actuated by piezoelectric actuator[7]. The compliant mechanism is used in the abovementioned stage in which the movements are guided by flexure hinges.

As we know, piezoelectric actuators have the advantages of high dynamic, high energy density and nearly unlimited resolution, etc., however, they also have the disadvantages of hysteresis behavior, nonlinear and drift and so on.

The characteristics of the hysteresis and nonlinear mean that the displacement output and voltage input is not in the proportional, and when a voltage input is applied to the actuator the displacement output will change slowly as time elapsed, which is called drift. As an example, figure 2(a) is shown that the hysteresis curve of the abovementioned ultraprecision stage for the displacement output in z direction, and drift curve is shown in figure 2(b) when a certain voltage is applied.

These disadvantages will limit severely the performances of the system such as undesirable inaccuracy or oscillations. Therefore, we think that it is impossible to achieve a limited position accuracy without the aid of further control technique to overcome these problems[8].

To obtain a high precision positioning, normally, the location of the gratings is controlled by a closed loop consisting of a high precision position sensor and a PID-controller. With the assumption of a linear transfer characteristic of the piezoelectric actuator, and meanwhile, the parameters of the controller are well adjusted, so the controller can have characteristics of a fast and sufficiently damped transient over the whole running range. However, this assumption on a linear transfer characteristic of the piezoelectric actuator is approximate since the piezoelectric actuator is driven by a high voltage to generate the longest displacement.

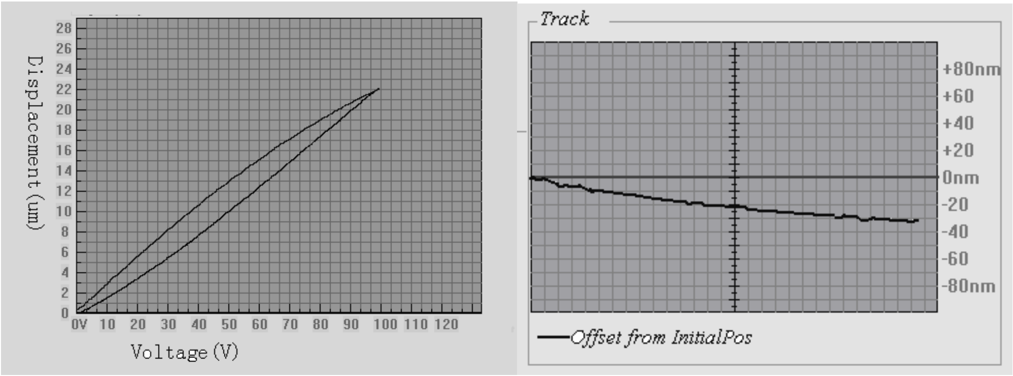

Fig. 2 (a) Hysteresis curve of the displacement output (b) Creep curve of the displacement output

3. DESIGN OF SINGLE NEURON ADAPTIVE PID CONTROL SYSTEM

As we know, the PID control is used in control engineering for a long time, and it has been widely accepted for many applications due to its simplicity in architecture. However, it is not very efficient for many nonlinear and time-varying systems, because the coefficients of PID are often fixed.

In this work, a single neuron adaptive PID control consists of PID control, an adaptive and self-learning of single neuron. An optimizing idea is mainly embodied in a learning rule of neural network to form different control algorithms, and by using these algorithms such as algorithm of supervising Hebb learning and making error square as performance index and so on, to modify weight value for determining an optimizing control sequence. So the single neuron algorithm is simple and often used in the on-line control condition.

A single neuron adaptive PID control structure[9] is shown in figure 3. The circuit enclosed with the dashed line is virtually constructed by a PC. An error signal between the desired and actual outputs is employed to update online adjustable parameters inside the controllers. To acquire high stability and nanometer resolution precision, here, a capacitive sensor with nanometer level measurement precision is used, the signal from the sensor is used as feedback for the controller with the single neuron adaptive PID algorithm.

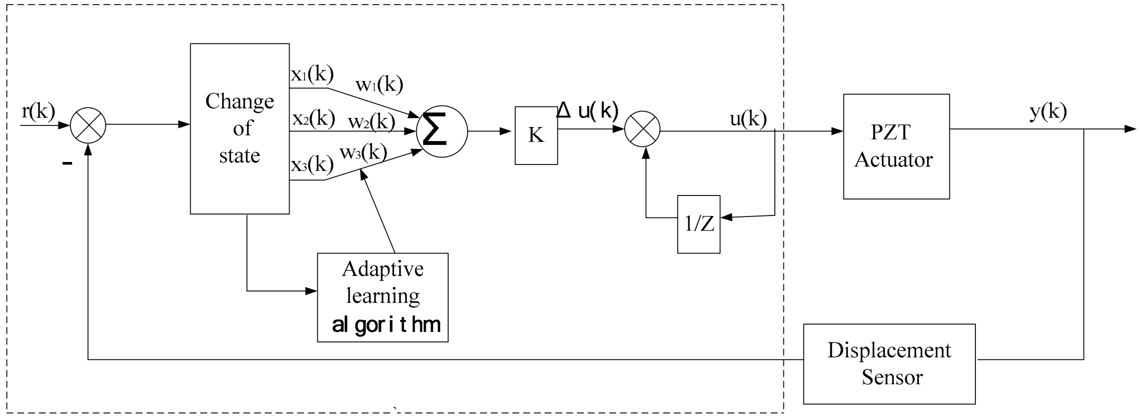

Fig. 3 structure of single neuron adaptive PID controller

We propose an adaptive single neuron-based PID controller, which $x_1(k)$ denotes the inputs, $e(k)$ is the error of the system, $x_2(k)$ is first-order difference of the error of the system, $\Delta e(k)$, and $x_3(k)$ is second-order difference of the error of the system, $\Delta e^2(k)$:

$$\left.\begin{aligned} x_1(k) &= e(k) = r(k) - y(k) \\ x_2(k) &= e(k) - e(k-1) \\ x_3(k) &= e(k) - 2e(k-1) + e(k-2) \end{aligned}\right\} \qquad (1)$$

Where $r(k)$ is the enactment reference signal of the system, $y(k)$ is the real-time signal gathered by the sensor, $w_i(k)$ is weight coefficient corresponding to $x_i(k)$ and K is proportional coefficient of the neuron. So output $u(k)$ of the neuron controller is as following:

$$u(k) = u(k-1) + K\sum_{i=1}^{3} w_i(k)x_i(k) \qquad (2)$$

Since it only needs to adjust the weight coefficients $w_i(k)$, which can form different control algorithms using different learning rules, a single neuron adaptive PID controller can implement adaptive and self-learning function. Here, we proposed a parameter of error square J, to value the performance of the system. J denoting performance index function is described as follows:

$$J=\frac{1}{2}[r(k+1)-y(k+1)]^2=\frac{1}{2}e(k+1)^2 \tag{3}$$

In order to minimize the performance index function, the gradient method is used, the difference of the weight factor Δw_i is written by

$$\Delta w_i=-\eta_i\frac{\partial J}{\partial w_i(k)}=-\eta_i\frac{\partial J}{\partial y(k+1)}\frac{\partial y(k+1)}{\partial u(k)}\frac{\partial u(k)}{\partial w_i(k)}=\eta_i x_1(k+1)\frac{\partial y(k+1)}{\partial u(k)}\frac{\partial u(k)}{\partial w_i(k)} \tag{4}$$

Using equation (1) and (2) to substitute into (4), then we can get

$$\left.\begin{aligned}\Delta w_1&=\eta_I Ke(k+1)x_1(k)\frac{\partial y(k+1)}{\partial u(k)}\\ \Delta w_2&=\eta_P Ke(k+1)x_2(k)\frac{\partial y(k+1)}{\partial u(k)}\\ \Delta w_3&=\eta_D Ke(k+1)x_3(k)\frac{\partial y(k+1)}{\partial u(k)}\end{aligned}\right\} \tag{5}$$

Since $\frac{\partial y(k+1)}{\partial u(k)}$ is often unknown, and it may be replaced approximately with a symbol function, namely, $\mathrm{sgn}(\frac{\partial y(k+1)}{\partial u(k)})$. The effect of loose may be compensated by adjusting learning rate η_i.

In order to ensure convergence and robustness, standardization learning algorithm should be adopted:

$$u(k)=u(k-1)+K\sum_{i=1}^{3}w_i^{'}(k)x_i(k) \tag{6}$$

$$w_i^{'}(k)=\frac{w_i(k)}{\sum_{i=1}^{3}|w_i(k)|} \tag{7}$$

After canonically settling above algorithms, we can get:

$$\left.\begin{aligned}
&u(k)=u(k-1)+K\sum_{i=1}^{3}w_i^{'}(k)x_i(k)\\
&w_i^{'}(k)=\frac{w_i(k)}{\sum_{i=1}^{3}|w_i(k)|}\\
&w_1(k+1)=w_1(k)+\eta_I Ke(k+1)x_1(k)\,\mathrm{sgn}(\frac{\delta y(k+1)}{\delta u(k)})\\
&w_2(k+1)=w_2(k)+\eta_P Ke(k+1)x_2(k)\,\mathrm{sgn}(\frac{\delta y(k+1)}{\delta u(k)})\\
&w_3(k+1)=w_3(k)+\eta_D Ke(k+1)x_3(k)\,\mathrm{sgn}(\frac{\delta y(k+1)}{\delta u(k)})\\
&\mathrm{sgn}(x)=\begin{cases}+1 & x\geq 0\\ -1 & x<0\end{cases}
\end{aligned}\right\}\qquad(8)$$

Where, η_P , η_I , and η_D is proportional learning rate, integral and differential learning rate, respectively. Besides, different learning rate is separately used in proportional (P), integral (I) and differential (D) control, so it is easy to adjust weight coefficient respectively according to the requirements. Moreover, their values may be confirmed by spot experiment or numeral simulations.

4. SIMULATION AND EXPERIMENT RESULTS

The simulation of the proposed algorithm and traditional PID algorithm by software Matlab is shown figure 4. From figure 4, it is seen that the traditional PID controller is overshoot, although the proposed controller has a longer adjusting time. We could get a much better control result by adjusting the PID parameter, some results of simulation also show that the single neuron adaptive PID controller have the higher accuracy and stronger adaptability with a satisfied control result .

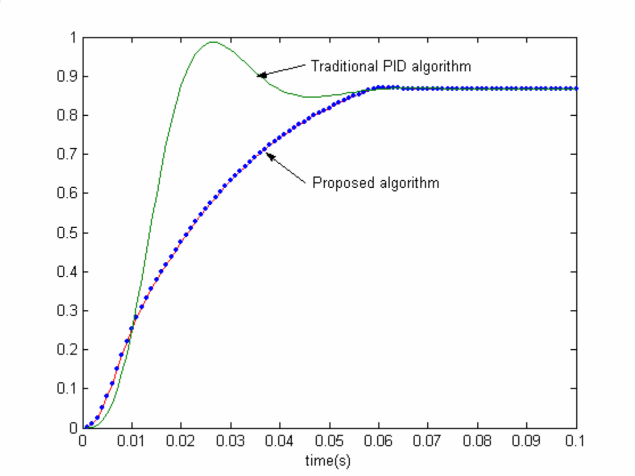

Fig. 4 simulations of the single neuron adaptive PID control algorithm and traditional PID algorithm

The single neuron adaptive control algorithm is realized by MS VC++. Actual step response of ultra-precision stage in the direction of z is shown in figure 5. It is seen from figure 5 that a stable positioning precision can reach <10 nanometers by means of the single neuron adaptive PID control, so it can meet the required precision for the tilting grating.

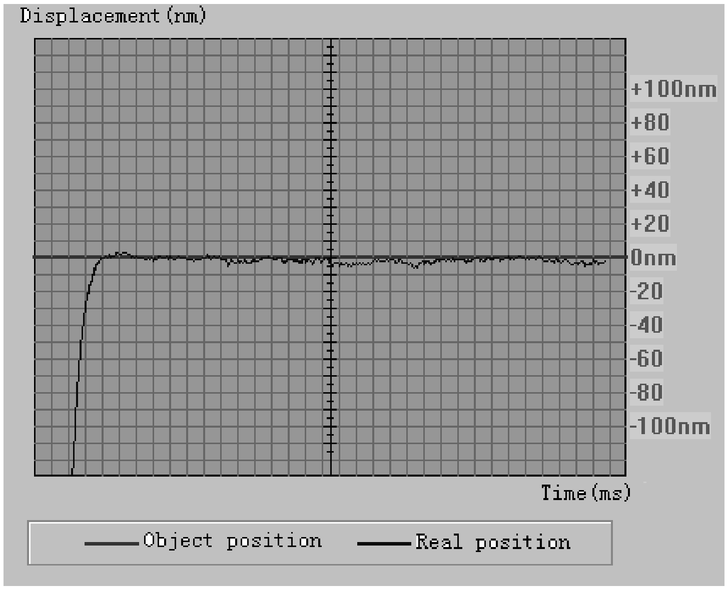

Fig. 5 The actual step response of ultraprecision stage in z direction

5. CONCLUSIONS

In this paper we developed a single neuron adaptive PID control system used in the grating tiling for the PW laser. The single neuron adaptive algorithm is proposed to improve the precision and robustness of the whole control system, and the algorithm can optimize the control parameters because of its taking the advantage of the neuron ability of self-organizing and self-learning. It is verified that this controller has good performance since the effect of the hysteresis is overcome and the desired control accuracy is guaranteed. In the future work, we will extend the controller present in this paper applied to other DOF in the ultraprecision stage. Besides, some parameters need to be adjusted such as the choice of the learning rate η_i , proportional coefficient K and so on.

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