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Active Vibration Suppression Based on Intelligent Control for a Long-range Ultra-precise Positioning System

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Abstract. Vibration is a significant factor that influences the performance of the long-range ultra-precise positioning system. Due to the intense nonlinearity and parameter uncertainties, it is difficult to eliminate the vibration by using a conventional PID controller. In this paper, the intelligent PID controller based on BP neural network with the ability of self-learning and strong robustness is introduced into the positioning system. Simulation and experiment are conducted and the results show that the vibration is effectively suppressed and the positioning accuracy has reached within 5.8nm.

Introduction

Long-range ultra-precise positioning system plays an important role in industrial equipment such as grating ruling machine, semiconductor manufacturing systems and assembly systems for photoelectronic products[1,2]. However, the performances of the positioning systems are influenced by many factors and vibration is one of the most significant. Vibration of an ultra-precise system can be mainly sorted into two types in view of its source: the external vibration and the internal vibration. The external vibration comes from the environment vibration such as ground and air, which can be easily isolated using passive vibration isolation systems[3,4,5]. The internal vibration, caused by motion of the system components, collision between system parts, slip-stick effect of friction and parameter uncertainties of the system, is difficult to be isolated owing to its characteristic of uncertainties and time-variance.

To reduce the influence of the internal vibration to the positioning quality, a vibration suppression method having a performance of fast response with no or small overshoot and robustness to object uncertainties is required. In this paper an intelligent PID controller based on BP neural network (BPNNPID), which has a simple structure and satisfies all the requirements above, is introduced into the system as an active vibration suppression method. Active vibration isolation has attracted much attention for its high effectiveness. Kapuria, S and Yasin, M.Y[6] utilized both classical constant gain velocity feedback and optimal control strategies to suppress the vibration of multilayered plates for contrast. Shahruz, S. M[7] proposed a novel active suppression approach based on disturbance observers for multi-input multi-output systems to eliminate the vibration in a multi-degree-of-freedom system. Mottershead, JE, Tehrani MG et al.[8] described a output feedback method using the measured receptances, which helps to get rid of the model reduction techniques and observers for the estimation of unmeasured states when designing a vibration suppression approach. Yong Xia and Ghasempoor, A[9] introduced an active and adaptive vibration control system based on neural network and digital signal processing techniques to minimize the vibration in a beam.

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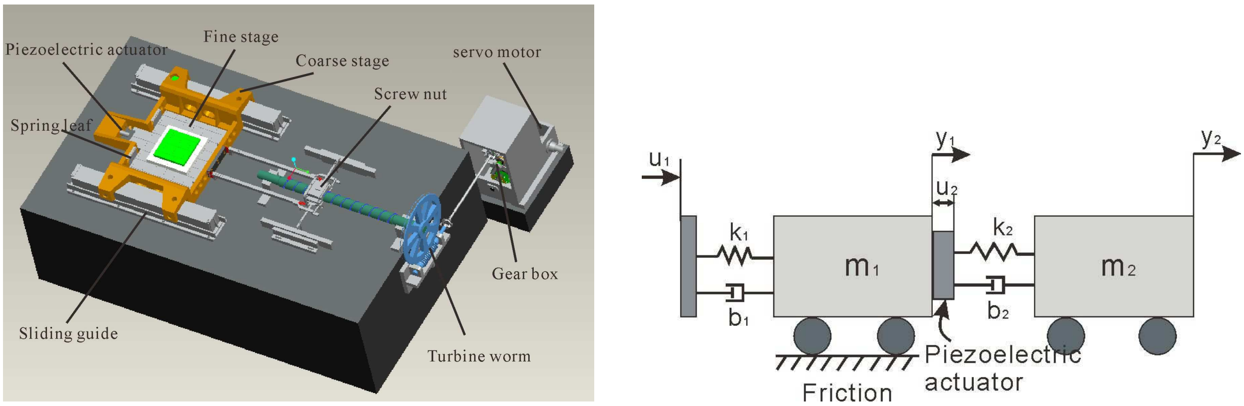
In this paper, first, the long-range ultra-precise positioning system and the dynamic model of the vibration are introduced. The second section constructs the active suppression system based on BPNNPID, the effect of which is further validated by simulation and experiment implemented in the Section 3. Finally, results and analysis are conducted in the conclusion.

Dynamic System of the Positioning System

The Physical Model. The long-range ultra-precise positioning system is composed of a coarse stage and a fine stage, as shown in Fig. 1(a). The coarse stage, aiming to realize a long range, is driven by a servo motor along the horizontal sliding guides. The transmission system includes a gear box, a turbine worm and a feed screw nut pair. The fine stage, hanging inside the coarse stage for nano-scale positioning, utilizes a piezoelectric actuator for its superior performance in high-accuracy motion control. The piezoelectric actuator is fixed between the coarse and fine stages by two preloaded springs as shown in Fig. 1(a).



(a) Architecture of the positioning system (b) Physical model of the positioning system

Figure 1. Architecture and physical model of the positioning system

Dynamics of Vibration. Fig. 1(b) shows the model of the positioning system and a summary of symbols used are as follows: m_1, m_2, the masses of the coarse and fine stage; $u_1(t)$, $u_2(t)$, the coarse and fine inputs; $y_1(t)$, $y_2(t)$, the outputs of the two stages. Moreover, it is assumed that k_1 and b_1 are the equivalent stiffness and equivalent damping coefficient of the transmission that connect to the coarse stage, while k_2 and b_2 are the same for the connections between the two stages. It is also assumed that vibration due to motion of transmission components, collisions and slip-stick effect of friction is part of $u_1(t)$, and vibration caused by the parameter uncertainties contributes to both $u_1(t)$ and $u_2(t)$. Thus, the dynamics of vibration with the positioning system can be expressed as

$$\begin{cases} m_1\ddot{y}_1 = k_1(u_1 - y_1) + b_1(\dot{u}_1 - \dot{y}_1) - k_2(y_1 + u_2 - y_2) - b_2(\dot{y}_1 + \dot{u}_2 - \dot{y}_2) - f \\ m_2\ddot{y}_2 = k_2(y_1 + u_2 - y_2) - b_2(\dot{y}_1 + \dot{u}_2 - \dot{y}_2) \end{cases} . \tag{1}$$

where f is the friction between the sliding guides and the coarse stage and it can be modeled as follows [10]:

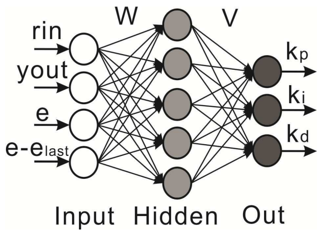
$$\begin{cases} f = \left\{ F_k \lambda(\dot{X}) + F_s(1 - \lambda(\dot{X})) \right\} sign(\dot{X}) \\ \lambda(\dot{X}) = \begin{cases} 0 & \left|\dot{X}\right| \le a,\ a > 0 \\ 1 & \left|\dot{X}\right| > a \end{cases} \end{cases} . \tag{2}$$

where F_k and F_s denote the dynamic friction force and the maximum static friction force, respectively; The artificial non-zero parameter a is used for numerical simulation to insure the convergence of the numerical integration algorithms.

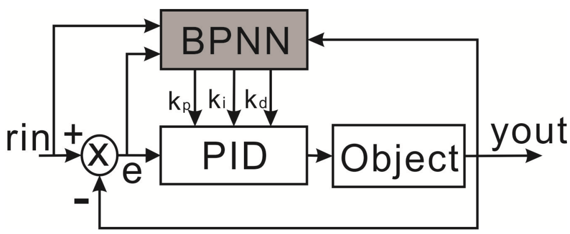
Eq.1 shows that vibration of the fine stage will always exist during the positioning period when the servo motor and piezoelectric actuator are working, which will greatly deteriorate the positioning performance.

Vibration Suppression Based on the BPNNPID Controller

Description of the BPNNPID. Considering the parameter uncertainties and strong nonlinearity of the system, the traditional PID controller cannot achieve good performance. The intelligent PID controller based on the back propagation neural network (BPNNPID) is effective in solving this problem owing to its ability of self-learning, which make it excellent for nonlinear system and robust to object uncertainties. Fig. 2 shows topological diagrams of the constructed BPNN and the BPNNPID controller. In the BP neural network, four input nodes including the reference input(*rin*), the displacement of the fine stage(*yout*), the tracking error(e) and the derivative of error(e-e_{last}) provide information of the vibration and the output nodes of the network are exactly the coefficients of the PID controller.



(a) Topological Diagram of BPNN



(b) Topological Diagram of BPNNPID

Figure 2. Topological Diagram of BPNN and BPNNPID

Online Learing Algorithm. As shown in Fig. 2, the law of the network can be expressed as follows.

Input layer: for each node i, the input and output are written as

$$y_{1,i} = x_{1,i},\ i = 1,2,3,4;\quad x_{1,i} \text{ is } rin,\ yout,\ e,\ \Delta e. \tag{3}$$

Hidden layer: for each node j, the input and output can be derived as

$$\begin{cases} y_{2,j} = F_1(x_{2,j}) = F_1(\sum_{i=1}^{4} y_{1,i} w_{i,j}) \\ F_1(x) = \dfrac{1}{1+e^{-x}} \end{cases}. \tag{4}$$

where $w_{i,j}$ is the updated input-hidden weighted coefficient.

Output layer: for each node k, the input and the output can be represented as

$$\begin{cases} y_{3,k} = F_2(x_{3,k}) = F_2(\sum_{j=1}^{5} y_{2,j} v_{j,k}) \\ F_2(x) = \dfrac{e^x - e^{-x}}{e^x + e^{-x}} \end{cases} . \tag{5}$$

where $v_{j,k}$ is the updated hidden-output weighted coefficient.

Update law: In order to eliminate the vibration, the weighted coefficients must be updated online for better suppression performance. The update law is derived according to the steepest descent approach and the error back-propagation algorithm, which can be expressed as follows:

$$\begin{cases} \Delta v_{jk} = -\eta \dfrac{\partial E}{\partial v_{jk}} = -\eta \dfrac{\partial E}{\partial y_{3,k}} \dfrac{\partial y_{3,k}}{\partial x_{3,k}} \dfrac{\partial x_{3,k}}{\partial v_{jk}} = \eta e F_2^{'} y_{2,j} \\ \Delta w_{ij} = -\eta \dfrac{\partial E}{\partial w_{ij}} = -\eta \dfrac{\partial E}{\partial y_{2,j}} \dfrac{\partial y_{2,j}}{\partial x_{2,j}} \dfrac{\partial x_{2,j}}{\partial w_{ij}} = -\eta F_1^{'} y_{1,i} \dfrac{\partial E}{\partial y_{2,j}} = \eta F_1^{'} y_{1,j} \sum_k (-\dfrac{\partial E}{\partial x_{3,k}}) \left(\dfrac{\partial (\sum_j v_{jk} y_{2,j})}{\partial y_{2,j}} \right) = \eta F_1^{'} y_{1,i} \sum_k e y_{2,j} F_2^{'} v_{jk} \end{cases} . \tag{6}$$

where η, the learning rate of the weighted coefficients; E the instantaneous square error of the positioning displacement.

Simulation and Experiments

Simulation. Numerical simulation is implemented to verify the practicability of the BPNNPID controller for vibration suppression. Gaussian noise is introduced into both $u_1(t)$ and $u_2(t)$ and the BPNNPID controller is active to keep the fine stage tracking the reference input with minimal error and vibration. Parameters are chosen as shown in Table 1.

Table 1. Parameters for simulation

Parameters	rin[nm]	m_1[kg]	m_2[kg]	k_1[N/m]	k_2[N/m]	b_1	b_2
Value	500	28.45	14.27	1.4399×10^6	4.5055×10^6	3.2954×10^3	748.7021

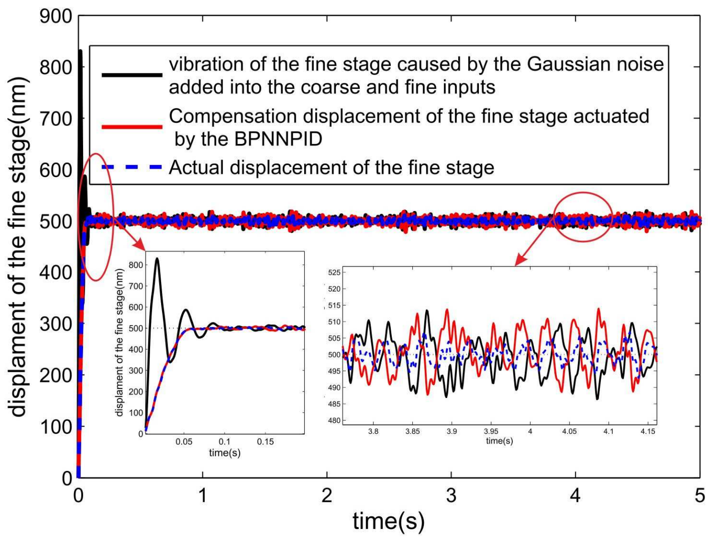
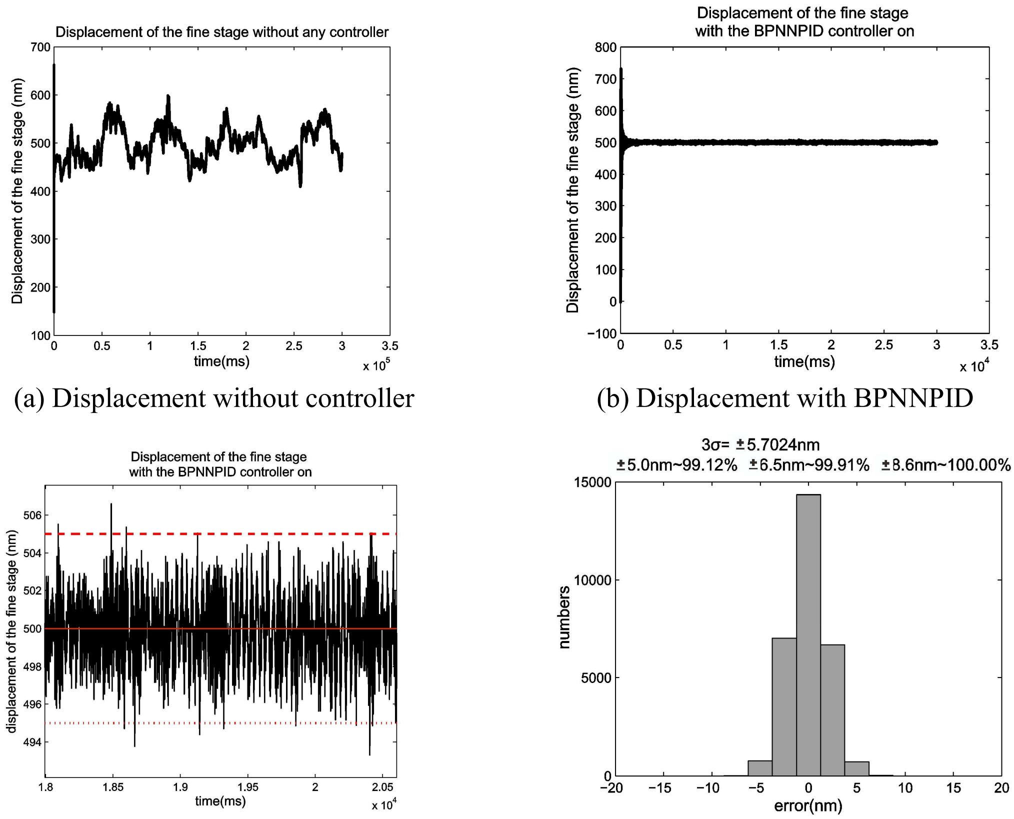


Figure 3. Simulation results of the BPNNPID for vibration suppression

As shown in Fig. 3, the vibration caused by the Gaussian noise stimulates a high overshoot which worsens the positioning performance and even makes it unstable. In addition, after a long time, vibration still exists and generates a relatively large tracking error. However, with the BPNNPID controller, it is so clear that overshoot is eliminated and vibration of the fine stage is suppressed by the compensation of the controller, which means the BPNNPID performs a high efficiency in suppressing the internal vibration of the positioning system.

Experiments. An experiment, with the reference input set as step signal valued 500nm, is conducted on a long-range ultra-positioning system and results are shown in Fig. 4. Fig .4(a) shows the displacement of the fine stage without any controller, where vibration seriously deteriorates the positioning quality. Fig .4(b) and Fig. 4(c) render the overall and detail view of the step response. It is obvious that, with the BPNNPID controller on, vibration is largely suppressed and the majority of tracking errors are within 5nm. Fig. 4(d) shows the statistical results of the errors and a positioning accuracy of 5.8nm has been achieved. Thus, the experiment results dovetail well with the simulation, which demonstrates that the vibration suppression method based on the intelligent BPNNPID controller performs well with high efficiency and strong robustness with friction and parameter uncertainties in nano-positioning systems.



(a) Displacement without controller

(b) Displacement with BPNNPID

(c) Details of the displacement with BPNNPID

(d) Tracking errors with BPNNPID

Figure 4. Results of the experiment with a reference step signal valued 500nm

Conclusion

In the long-range ultra-positioning system, vibration caused by motion of the system components, collision between system parts, slip-stick effect of friction and parameter uncertainties seriously influence the positioning performance and is difficult to be eliminated due to its characteristic of strong nonlinearity, randomness and time-variance. In order to solve this problem, an active vibration suppression method based on intelligent BPNNPID controller is introduced into the system in this paper. A BP neural network is constructed to adjust the coefficients of the PID controller online. Simulations and experiments have been conducted to verify the efficiency of the suppression method and both the results show that the BPNNPID controller can significantly suppress the internal vibration of the positioning system, and perform well with robustness to the parameter uncertainties. With the active vibration suppression method, the long-range ultra-precise positioning system has achieved a positioning accuracy of 5.8nm.

References

[1] Santosh Devasia, Evangelos Eleftheriou and S. O. Reza Moheimani: A Survey of Control Issues in Nanopositioning, IEEE Transactions on Control Systems Technology Vol. 15 (2007), p. 802-823

[2] Wahyudi, Kaiji Sato and Akira Shimokohbe: Characteristics of practical control for point-to-point (PTP) positioning systems Effect of design parameters and actuator saturation on positioning performance, Precision Engineering Vol. 27 (2003), p. 157-169

[3] Zhao PF, Luo J, Zhou ZB and Tang JX: Ultra-low frequency passive vertical vibration isolation system, Science in China Series A-Mathematics Physics Astronomy Vol. 47(1999), p. 660-665

[4] Garoi F, Winterflood J, Ju L, Jacob J and Blair DG: Passive Vibration Isolation Using a Roberts Linkage, Review of Scientific Instruments Vol. 74(2003), p. 3487-3491

[5] Li CA, Wang SL, Kang L, Lei S and Yu QB: Two-Terminal Manipulation of Masses: Application to Vibration Isolation of Passive Suspensions, Journal of Vibroengineering Vol. 12(2010), p. 225-236

[6] Kapuria, S and Yasin, M.Y: Active vibration suppression of multilayered plates integrated with piezoelectric fiber reinforced composites using an efficient finite element model, Journal of Sound and Vibration Vol. 329(2010), p. 3247-3265

[7] Shahruz, S. M: Active Vibration Suppression in Multi-degree-of-freedom Systems by Disturbance Observers, Journal of Vibration and Control Vol.15(2009), p. 1207-1228

[8] Mottershead, JE, Tehrani MG, James S and Ram YM: Active vibration suppression by pole-zero placement using measured receptances, Journal of Sound and Vibration Vol. 311(2008), p. 1391- 1408

[9] Yong Xia and Ghasempoor, A: Active Vibration Suppression Using Neural Networks, World Congress on Engineering, WCE 2009 Vol. 2(2009), p. 1627-1632

[10] Southward SC and Radcliff CJ: Robust nonlinear stick-slip friction compensation, Journal of Dynamic Systems Measurement and Control Vol. 113(1991), p. 639-645

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