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High Performance Control of High-acceleration Motions Based on Time-domain Relay Feedback Technique

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Abstract— **This paper focuses on proposing an easily-implemented control method for high-acceleration point-to-point motions. The control algorithm used here to handle the disturbances consists of a model-based feedforward controller, a pole-placement PD controller and a disturbance observer. Then, a fast time-domain identification technique is implemented to give the accurate model parameters, which can be directly utilized in the control algorithm. The method avoids the complicated parameters tuning process, which would be attractive in the industrial application. Experiments are carried out on a permanent magnet linear synchronous motor (PMLSM) and the results demonstrate that the proposed method is capable of achieving high-precision and fast positioning by reducing the tracking error and overshoot.**

I. INTRODUCTION

With the rapid development of semiconductor industry, the advanced manufacturing and packaging equipments are required to satisfy the demands for high acceleration and high precision [1], [2]. Under the condition of high acceleration, fast positioning of the point-to-point motion is often restricted by many disturbances, such as nonlinear friction, resonance uncertainties, cable tension and other factors. In order to achieve fast positioning, many researchers have paid attention to the servo controller design and proposed a large number of algorithms.

Among the existing algorithms, the feedback PID controllers with various tuning techniques [3]–[6] are the most popular approaches for trying to meet the above-mentioned demands in real application. But it is necessary to point out that parameters tuning could be time-consuming, because the parameters of PID controller are commonly tuned by trial and error method which mostly relies on the engineer's experience. Therefore, the advanced controllers are explored to further improve the servo performance, such as disturbance observer (DOB) [7]–[9], iterative learning control [10], H_∞-based robust control [11], adaptive robust control [12], variable structure control [13] and so on. With the appropriate parameters, all the advanced algorithms can be used with different degrees of servo performance improvement. However, parameters tuning of the advanced controllers requires much more effort than that of PID controllers. One thing to note here is that most of the advanced controllers are the model-based ones. The accurate identified value of system parameters contributes to obtain more precise model of the system and hence easily improves the servo performance of the controller. Otherwise, parameters tuning is also a time-consuming process. The parameters of the model-based controllers could be hardly tuned to achieve better performance when the identification parameters are far away from that of the employed plant. As a result, the model identification techniques are urgently studied.

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The relay-based feedback technique (RFT) is widely explored due to its simplicity and effectiveness. The basic idea of RFT is to estimate the model parameters on the basis of the oscillations excited by the relay modular and then design the model-based controller. In recent years, RFT was successfully applied to servo mechanical system and greatly improve the servo performance [14]–[17]. The conventional analysis tools of the relay feedback tests were describing function (DF) method in frequency domain. The identification values with DF method could be less accurate owing to its own approximation. To deal with the problem, Chen [18] and Liu [19] proposed a time-domain based approach to identify servo mechanical system. The time-domain identification method effectively prevents the approximation, due to the exact expressions of the periods and amplitudes of the oscillations under relay feedback test can be perfectly derived. Therefore, an improved time-domain identification method with position signal as the feedback is utilized here to obtain more accurate model parameters within a few minutes. Based on the identified model parameters, a high-performance control algorithm consists of a PD controller, a feedforward controller and a disturbance observer is implemented to achieve the fast and high-precision positioning under the high acceleration condition.

The outline of this paper is as follows. Section II discusses the model of the servo mechanical system and fast identification method. The control structure and design approach are thoroughly explained in section III. Experiments are conducted on the PMLSM-driven servo mechanical system to validate the simplicity and effectiveness of the proposed method in section IV. Section V summarizes the paper.

II. SYSTEM IDENTIFICATION

A. Modeling of the PMLSM-driven System

The permanent magnet linear synchronous motor is widely applied to achieve higher requirements in semiconductor manufacturing equipments. The PMLSM here is a voltage-controlled three-phase iron-core permanent magnet linear synchronous motor, which drives a positioning table by linear cross-rollers to achieve fast positioning and high-precision tracking performance. Regardless of the negligible Coulomb friction, the dynamics model can be expressed as

$$m\ddot{x}+B\dot{x}=k_t u-F_d, \tag{1}$$

where m is the mass of the slider, B is the viscous coefficient, $\ddot{x}$ and $\dot{x}$ are the acceleration and velocity respectively, k_t is the thrust coefficient, u is the voltage input, and F_d is the external disturbances besides the viscous friction. Denote $\alpha=m/k_t$, $\beta=B/k_t$, and $f_d=F_d/k_t$, the established model can be written as

$$\alpha\ddot{x}+\beta\dot{x}=u-f_d. \tag{2}$$

Accordingly, the transfer function from u to x is

$$G(s)=\frac{X(s)}{U(s)}=\frac{k}{(\tau s+1)s}, \tag{3}$$

where $X(s)$ and $U(s)$ are the Laplace transformation of x and u respectively, $k=1/\beta$, and $\tau=\alpha/\beta$.

B. Parameters Identification

In this subsection, a time-domain relay-based identification method in position loop, which is developed by the references [17] and [19], is utilized to obtain a more accurate model parameters. Fig. 1 shows the block diagram of relay feedback test with additional dead time.

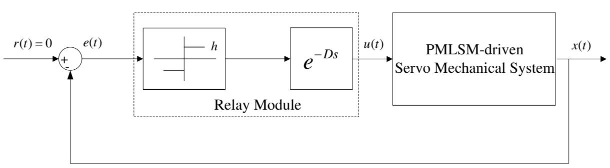

Fig. 1. Block diagram of relay feedback test

Under the excitation of the amplitude $h=0.2$ V and the artificial dead time $D=0.02$ s, the oscillation amplitude $x(t)$ and the oscillation half period T_u are measured as 0.8887 mm and 0.1471 s respectively. With the time-domain relay-based identification method, the model parameters of the PMLSM-driven servo mechanical system are precisely calculated from

$$\begin{cases} kh(t_1-\tau+\tau e^{-t_1/\tau})=x \\ kh(1-e^{-T_u/\tau})-2kh(1-e^{-(T_u-t_1-D)/\tau})=0 \\ kh(T_u-\tau+\tau e^{-T_u/\tau})-2hk(T_u-t_1-D-\tau \\ \qquad\qquad +\tau e^{-(T_u-t_1-D)/\tau})=2x \end{cases}, \tag{4}$$

where t_1 is the intermediate variable.

Therefore, the identified values of τ and k can be quickly and accurately obtained as $\hat{\tau}=0.0922$ s and $\hat{k}=1662.95$ Vs/mm in a short time.

III. CONTROL STRUCTURE

Based on the established model, a high-performance controller as is shown in Fig. 2 is implemented to achieve fast positioning under high acceleration condition, which is comprised of a model-inverse feedforward controller, a pole-placement PD controller and a disturbance observer. The feedforward controller is to improve the system dynamics, the PD controller is to implement the feedback control for stabilizing the system and the disturbance observer is to suppress the external disturbances. Hence, (2) can be expressed as

$$\alpha\ddot{x}+\beta\dot{x}=u_{ff}+u_{pd}-u_{dob}-f_d, \tag{5}$$

where u_{ff}, u_{pd} and u_{dob} are respectively the outputs of the feedforward controller, the PD controller and the disturbance observer.

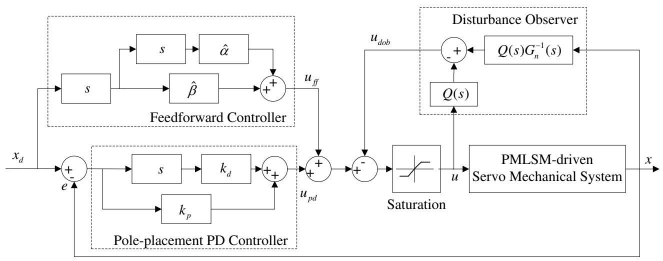

Fig. 2. The proposed control algorithm

A. Model-inverse Feedforward controller

The output of feedforward controller can be written as

$$u_{ff}=\hat{\alpha}\ddot{x}_d+\hat{\beta}\dot{x}_d, \tag{6}$$

where $\dot{x}_d$ is the reference profile velocity, $\ddot{x}_d$ is the reference profile acceleration, $\hat{\alpha}$ and $\hat{\beta}$ are the coefficients of the feedforward controller, respectively. With the model inverse approach, the coefficients of the feedforward controller are

$$\hat{\alpha}=\hat{\tau}/\hat{k}, \tag{7}$$

$$\hat{\beta}=1/\hat{k}. \tag{8}$$

B. Pole-placement PD controller

The output of PD controller can be described as

$$u_{pd}=k_p e+k_d\dot{e}, \tag{9}$$

where k_p is the proportional coefficient and k_d is the derivative coefficient. Substituting (6) and (9) into (5), we get

$$\hat{\alpha}\ddot{e}+(\hat{\beta}+k_d)\dot{e}+k_p e=u_e+f_d+u_{dob}, \tag{10}$$

where $u_e=(\alpha-\hat{\alpha})\ddot{x}+(\beta-\hat{\beta})\dot{x}$, $e=x_d-x$ is the tracking error, x_d and x are the reference profile position and the measured position respectively.

Suppose that the external disturbances and internal interferences could be suppressed completely by the disturbance observer, (10) becomes

$$\hat{\alpha}\ddot{e}+(\hat{\beta}+k_d)\dot{e}+k_p e=0. \tag{11}$$

Considering the ability to assign the poles at desired position in complex plane, the pole-placement method is usually used to design the parameters of the PD controller in real applications. Take p_1 and p_2 as poles of the transfer function, k_p and k_d can be written as

$$k_p=p_1 p_2\hat{\tau}/\hat{k}, \tag{12}$$

$$k_d=-(1+(p_1+p_2)\hat{\tau})/\hat{k}. \tag{13}$$

C. Disturbance observer

Disturbance observer is usually utilized to improve the performance of the system against uncertainties and disturbances by subtracting its estimate, which is obtained by comparing the control signal with the plant output. In this subsection, DOB is utilized for suppressing the disturbances to further improve the performance of the PMLSM-driven servo mechanical system.

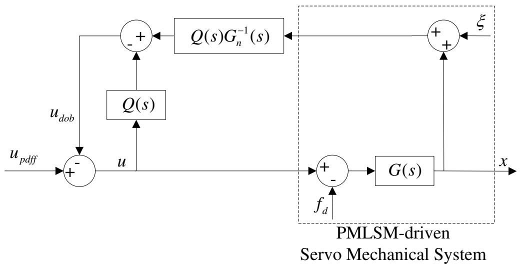

Fig. 3. The schematic diagram of disturbance observer

On the basis of the DOB schematic diagram as shown in Fig. 3, the plant output x can be expressed as

$$x = \frac{G(s)[G_n(s)u_{pdff} - G_n(s)(1-Q(s))f_d - Q(s)\xi]}{G_n(s)+Q(s)(G(s)-G_n(s))}, \quad (14)$$

where $G(s)$ is the transfer function of the PMLSM-driven servo mechanical system, $G_n(s)$ is the identified model, u_{pdff} is the sum of u_{pd} and u_{ff}, $Q(s)$ is a low-pass filter, and ξ is the measurement noise.

The low-pass filter $Q(s)$ determines the performance of the disturbance observer. Above the cutoff frequency of $Q(s)$, $Q(s)=0$ is achieved. Hence, the high-frequency measurement noise is attenuated. On the contrary, $Q(s)=1$ is achieved below the cutoff frequency of $Q(s)$, Hence, the low-frequency disturbances are attenuated. Considering the platform characteristics, $Q(s)$ is designed to the form that the numerator is of first order and the denominator is of third order [20]. Then $Q(s)$ is written as

$$Q(s) = \frac{3\tau_1 s+1}{{\tau_1}^3 s^3 + 3{\tau_1}^2 s^2 + 3\tau_1 s + 1}, \quad (15)$$

where τ_1 is the time constant of $Q(s)$.

Considering the contradiction between the high-frequency measurement noise and the low-frequency disturbances, the time constant τ_1 is chosen by two criteria: One is the selection of τ_1 should guarantee that the cutoff frequency of $Q(s)$ is below the natural frequency of the employed platform. The other is that τ_1 should be possibly small by taking full account of the employed platform characteristics.

Therefore, the output of the employed planform with the proposed control algorithm is

$$\begin{aligned} x = &\frac{G(s)G_n(s)(\hat{\alpha}s^2+\hat{\beta}s+k_p+k_d s)x_d}{G_n(s)+Q(s)(G(s)-G_n(s))+G(s)G_n(s)(k_p+k_d s)} \\ &- \frac{G(s)[G_n(s)(1-Q(s))f_d+Q(s)\xi]}{G_n(s)+Q(s)(G(s)-G_n(s))+G(s)G_n(s)(k_p+k_d s)}. \end{aligned} \quad (16)$$

From (16), It also can be seen that if the identification parameters equal to the ones of the employed plant, i.e. $G(s)=G_n(s)$, then $x=x_d$. However, it is difficult to achieve in reality. When the identification parameters are relatively close to that of the PMLSM-driven servo mechanical system, parameters of the proposed control algorithm can be tuned simply to achieve better performance. Otherwise, it could be time-consuming for parameters tuning. To deal with the problem, the advantages of the proposed relay-based control method will be detailed in the next section.

IV. EXPERIMENTAL STUDIES

A. Experimental Setup

The experiments were implemented on the Y-axis of servo system as shown in Fig. 4. The positioning control system consists of a PC-based dSPACE control system, an X-Y positioning stage, actuating device and so on.

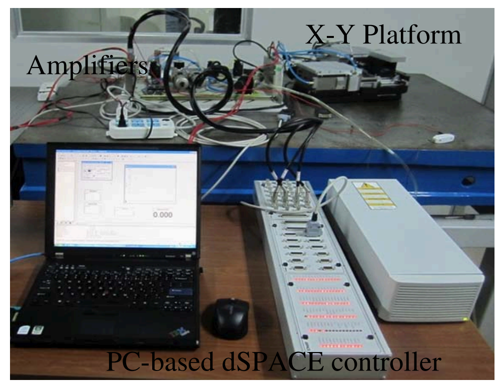

Fig. 4. Setup of the PMLSM-driven servo mechanical system

The X-Y table positioning mechanism is designed for a semiconductor wire-bonding equipment. By feeding appropriate three-phase current to the coils, the PMLSMs drive the bonding mechanical system through cross-roller linear guides. An equivalent load of 2 kg is mounted on the stage instead of the bonding head and its assembly accessories. The first natural frequency of Y-axis is about 238 H_z and that of X-axis is about 248 Hz. Each axis is equipped with an incremental linear encoder (Heidenhain LIF 471) with the resolution of 0.1 um after quadruplication. The proposed algorithm is employed by the dSPACE DS1103 DSP board together with MATLAB Real-Time Workshop with sampling time of 0.1 ms.

B. Point-to-Point Movements

In this subsection, the effectiveness of the proposed method are verified by comparing the servo performances of three control strategies in point-to-point motions: the PD controller (PD), the PD controller plus feedforward controller (PDFC) and the proposed DOB-based controller (PDFC-DOB). The values of the relevant controller parameters for the experiments are listed in Table 1.

The reference position profile with a reciprocating stroke of 0.1 inch (2.54 mm) as shown in Fig. 5 is generated by

TABLE I

VALUES OF THE RELEVANT CONTROLLER PARAMETERS

Pole-placement PD controller:	
	$p_1 = -400$ rad/s
	$p_2 = -400$ rad/s
Feedforward controller:	
	$\hat{\alpha} = 0.00005544$ Vs^2/mm
	$\hat{\beta} = 0.000060134$ Vs/mm
Disturbance Observer:	
	$\tau_1 = 0.0005$ s

the asymmetric S-curve. The planning time of the reference profile is 12 ms while the maximum planning acceleration and deceleration are 9.1 g (1 g = 9.806 m/s^2) and 7.2 g respectively.

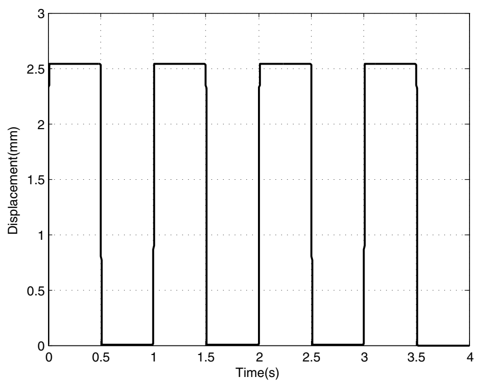

Fig. 5. The reference reciprocating stroke

The tracking performance is first analyzed under the above-mentioned three control strategies as shown in Fig. 6 - Fig. 8. It can be seen that the feedforward controller tremendously improves the system dynamics. The maximum tracking error of the forward stroke is reduced from 351.2 um to 7.9 um and that of the backward stroke is also reduced from 348.1 um to 10.0 um. The proposed controller further improves the tracking performance by efficiently suppressing the disturbances. The maximum tracking errors of the the forward and backward stroke are reduced to 2.0 um and 2.6 um respectively.

The overshoots of the forward stroke and backward stroke under different controllers are illustrated in Fig. 9 - Fig. 14. The figures show that the overshoots are greatly decreased by the feedforward controller. Compared with the PD controller, the maximum overshoot is reduced from 244.7 um (248.3 um) to 6.8 um (10 um). Owing to compensating the biased characteristics with the proposed controller, the forward and backward overshoots are both 1.3 um, as shown in Fig. 13 and Fig. 14.

Positioning time is also a meaningful index in the industrial applications. Positioning time is defined as the time from the beginning of the reference profile to the moment that the tracking error fully converges to the error band while the displacement is close proximity to the reference position. The error band is set to 2 um according to the requirement of the semiconductor manufacturing equipments. The positioning

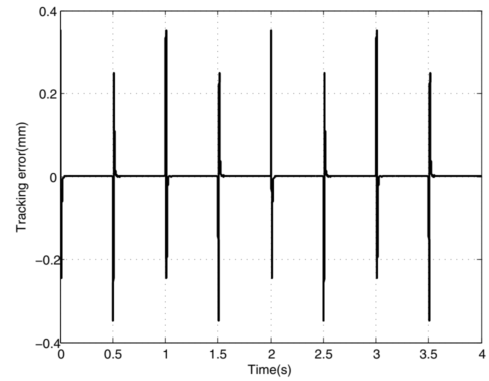

Fig. 6. Tracking error under PD controller

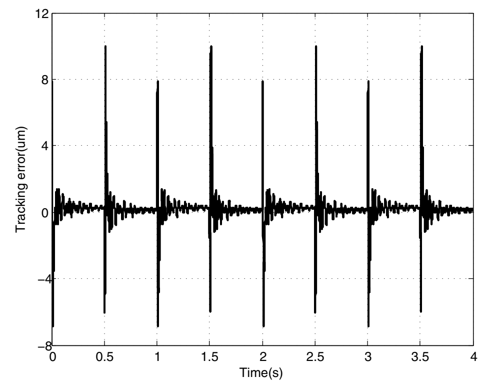

Fig. 7. Tracking error under PDFC controller

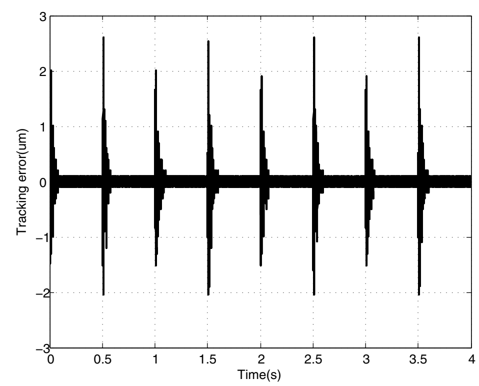

Fig. 8. Tracking error under the proposed controller

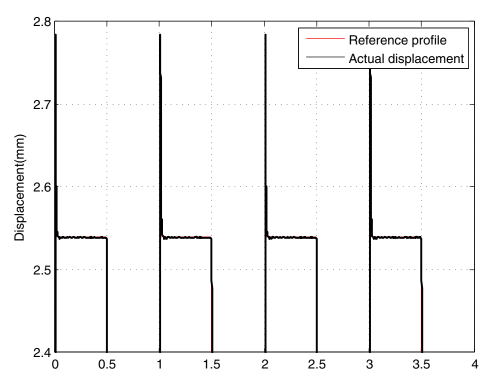

Fig. 9. Overshoot of the forward stroke under PD controller

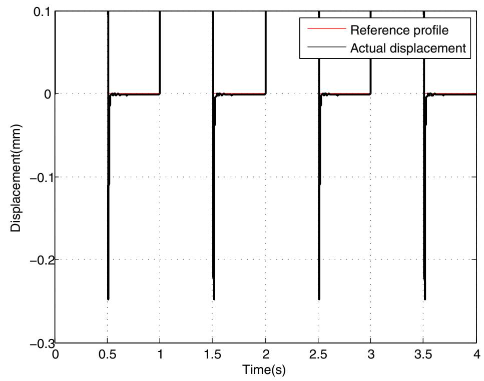

Fig. 10. Overshoot of the backward stroke under PD controller

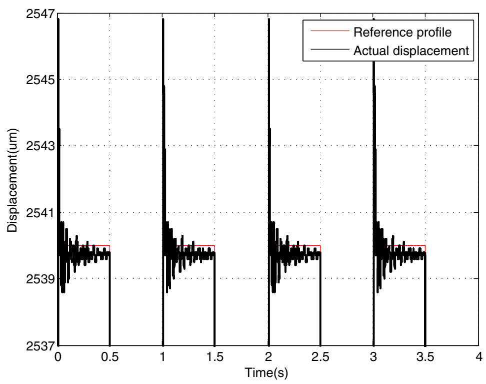

Fig. 11. Overshoot of the forward stroke under PDFC controller

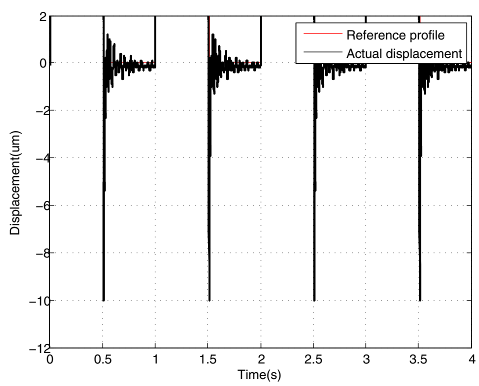

Fig. 12. Overshoot of the backward stroke under PDFC controller

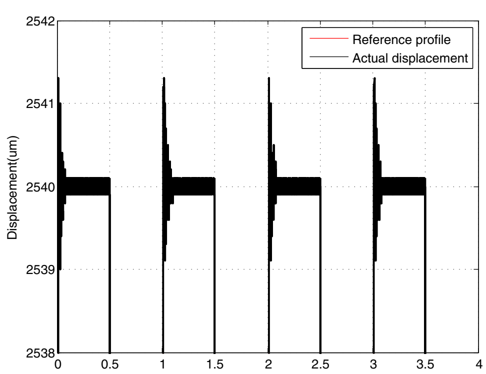

Fig. 13. Overshoot of the forward stroke under the proposed controller

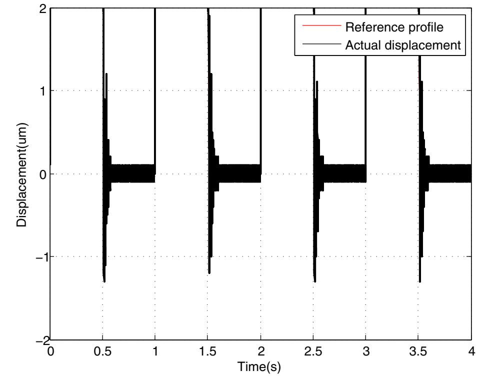

Fig. 14. Overshoot of the forward stroke under the proposed controller

times under the three controllers are shown in Fig.15 - Fig.18. The positioning times of the PD controller are 73.5 ms and 94.9 ms respectively and obviously longer than the planning time. With introduction of the feedforward controller, the positioning times of the PDFC controller are reduced by nearly 70 %. Since the external disturbances are effectively suppressed by the disturbance observer, the positioning time is further reduced from 23.9 ms (26.0 ms) to 11.4 ms (11.5 ms).

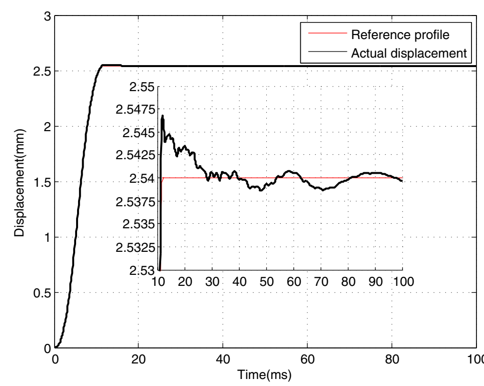

Fig. 15. Forward positioning time under PDFC controller

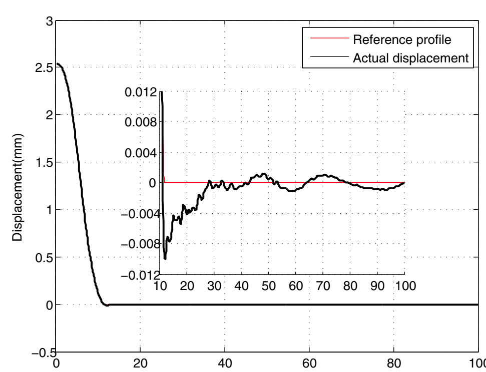

Fig. 16. Backward positioning time under PDFC controller

In brief, it can be concluded that the proposed controller can achieve high-precision and fast positioning of the

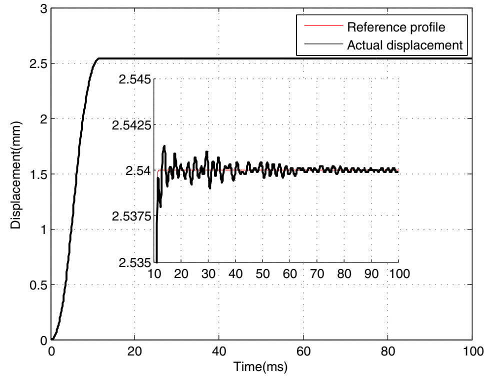

Fig. 17. Forward positioning time under the proposed controller

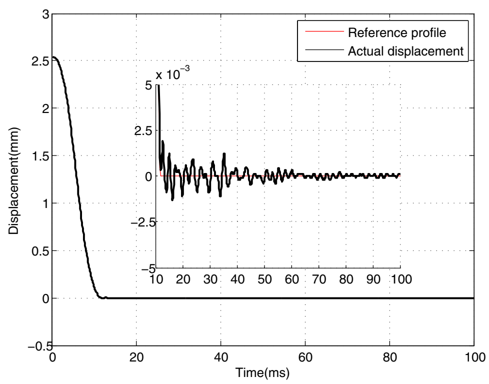

Fig. 18. Backward positioning time under the proposed controller

PMLSM-driven servo mechanical system by tremendously reducing the tracking error and overshoot.

V. CONCLUSIONS

An easily-implemented control method for high-acceleration point-to-point motions is proposed in this paper. It combines the model-inverse feedforward controller, the pole-placement PD controller and the disturbance observer to handle the system disturbances. The control parameters of the feedforward controller are directly calculated out by the identified model parameters, which are provided by a fast time-domain relay feedback technique in position loop. Once the DOB parameter has been chosen by the two criteria, p_1 and p_2 are only tuned for determining the overall performance of the controlled system. Experimental results demonstrate that the proposed method avoids the complicated parameters tuning process and greatly improves the tracking error, overshoot and positioning time.

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REFERENCES

[1] Z. Z. Liu, F. L. Luo, and M. A. Rahman, "Robust and precision motion control system of linear-motor direct drive for high-speed xy table positioning mechanism," *Industrial Electronics, IEEE Transactions on*, vol. 52, no. 5, pp. 1357–1363, 2005.

[2] H. Ding and Z. Xiong, "Motion stages for electronic packaging design and control," *Robotics & Automation Magazine, IEEE*, vol. 13, no. 4, pp. 51–61, 2006.

[3] J. Ziegler and N. Nichols, "Optimum settings for automatic controllers," *trans. ASME*, vol. 64, no. 11, 1942.

[4] R. Krohling, H. Jaschek, and J. Rey, "Designing pi/pid controllers for a motion control system based on genetic algorithms," in *Intelligent Control, 1997. Proceedings of the 1997 IEEE International Symposium on*. IEEE, 1997, pp. 125–130.

[5] J. Carvajal, G. Chen, and H. Ogmen, "Fuzzy pid controller: Design, performance evaluation, and stability analysis," *Information Sciences*, vol. 123, no. 3, pp. 249–270, 2000.

[6] R. Sanchis, J. A. Romero, and P. Balaguer, "Tuning of pid controllers based on simplified single parameter optimisation," *International Journal of Control*, vol. 83, no. 9, pp. 1785–1798, 2010.

[7] Z.-J. Yang, H. Tsubakihara, S. Kanae, K. Wada, and C.-Y. Su, "A novel robust nonlinear motion controller with disturbance observer," *Control Systems Technology, IEEE Transactions on*, vol. 16, no. 1, pp. 137–147, 2008.

[8] M.-T. Yan and Y.-J. Shiu, "Theory and application of a combined feedback–feedforward control and disturbance observer in linear motor drive wire-edm machines," *International Journal of Machine Tools and Manufacture*, vol. 48, no. 3, pp. 388–401, 2008.

[9] B. K. Kim, W. K. Chung, and K. Ohba, "Design and performance tuning of sliding-mode controller for high-speed and high-accuracy positioning systems in disturbance observer framework," *Industrial Electronics, IEEE Transactions on*, vol. 56, no. 10, pp. 3798–3809, 2009.

[10] J. Wu and H. Ding, "Iterative learning variable structure controller for high-speed and high-precision point-to-point motion," *Robotics and Computer-Integrated Manufacturing*, vol. 24, no. 3, pp. 384–391, 2008.

[11] L. Bingyou, "Research on h infinity robust tracking controller for permanent magnet synchronous motor servo system," in *Information Engineering and Computer Science, 2009. ICIECS 2009. International Conference on*. IEEE, 2009, pp. 1–5.

[12] J. Zhong and B. Yao, "Adaptive robust precision motion control of a piezoelectric positioning stage," *Control Systems Technology, IEEE Transactions on*, vol. 16, no. 5, pp. 1039–1046, 2008.

[13] A. Sabanovic, "Variable structure systems with sliding modes in motion controlła survey," *Industrial Informatics, IEEE Transactions on*, vol. 7, no. 2, pp. 212–223, 2011.

[14] K. K. Tan, T. Lee, S. N. Huang, and X. Jiang, "Friction modeling and adaptive compensation using a relay feedback approach," *Industrial Electronics, IEEE Transactions on*, vol. 48, no. 1, pp. 169–176, 2001.

[15] D. Pu, J. Wu, Z. Xiong, X. Sheng, and H. Ding, "Nonlinear analysis and parameters identification of servo mechanism with relay feedback," *Assembly Automation*, vol. 30, no. 3, pp. 221–227, 2010.

[16] W. Jianhua, L. Jia, X. Zhenhua, and D. Han, "A relay-based method for servo performance improvement," *Mechatronics*, vol. 21, no. 6, pp. 1076–1086, 2011.

[17] C. Liu, J. Liu, J. Wu, and Z. Xiong, "High precision embedded control of a high acceleration positioning system," in *Intelligent Robotics and Applications*. Springer, 2012, pp. 551–560.

[18] S.-L. Chen, K. K. Tan, and S. Huang, "Identification of coulomb friction-impeded systems with a triple-relay feedback apparatus," *Control Systems Technology, IEEE Transactions on*, vol. 20, no. 3, pp. 726–737, 2012.

[19] J. Liu, J. Wu, Z. Xiong, and X. Zhu, "Servo system identification using relay feedback: A time-domain approach," *Transactions of the ASME-B-Journ Manufacturing Science Engineering*, vol. 134, no. 6, p. 061012, 2012.

[20] T. Umeno, T. Kaneko, and Y. Hori, "Robust servosystem design with two degrees of freedom and its application to novel motion control of robot manipulators," *Industrial Electronics, IEEE Transactions on*, vol. 40, no. 5, pp. 473–485, 1993.