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A Model Reference Adaptive PID Control for Electromagnetic Actuated Micro-positioning Stage

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Abstract— **This paper presents a model reference adaptive PID controller for controlling a novel compliant flexures-based XY micro-positioning stage driven by electromagnetic actuators. The stage is specially designed by employing double four-bar parallelogram flexures and four non-contact electromagnetic force actuators to realize the kinematic decoupling and force decoupling respectively. Based on preliminary open loop experiments and simple PID controller based close-loop experiments, we found that the system is with typical hysteresis and nonlinear characteristics. As model reference adaptive control techniques possess great advantages to tackle robustness issues of nonlinear and model uncertainty systems, it is designed and adopted to control the micro-manipulator system. At first, a model reference adaptive PID controller design process is introduced. Then control parameters are systematically tuned based on intuitive desired performance and robustness. At last, experimental results verify the process for controlling the micro-positioning stage, which shows that the adopted controller can drive the mobile stage to track the desired reference path exactly.**

I. INTRODUCTION

Compliant mechanisms with flexure hinges can provide with very high precision in performing precise manipulation and assembly task, therefore they are widely applied in micro/nano world. Replacing with conventional mechanical joints, flexure hinges can provide more ideal high-precision motions since they have advantages including no backlash, no friction losses, no need for lubrication, vacuum compatibility, ease of fabrication and basically no need for assembling. Many compliant mechanisms with flexural hinges can be designed and fabricated to realize precise micro/nano-positioning tasks [1]- [4].

For more applications such as IC assembly or biological cell manipulation, a large motion range is preferred for each motion axis. In order to achieve both large motion range, high resolution in positioning, and simple controller design, considering the small payload of the maglev system in the normal gravity environment, we need not only to construct a kinematic decoupled structure with compliant flexure hinges, but also need to eliminate force contact by using non-contact or a frictionless force generated between the moving platform and the stator. Several kinds of actuators can realize non-contact or frictionless forces, such as electromagnetic force and air bearings, but air bearings are not suitable for a high vacuum environment. There are many advantages associated with electromagnetic actuators in terms of no contamination, no friction, fast response, large travel range, and low cost [5]- [7]. Moreover, comparing with the maglev micro positioning systems [8], the electromagnetic driven micro manipulator with flexure-based mechanism can have a large load capability as well as a good precision.

Although the compliant flexures based electromagnetic actuators driven system possesses many advantages, the varying air gap between the actuators and the armatures causes severe nonlinear and hysteresis characteristics. The nonlinear and hysteresis characteristics of the actuators bring much troubles to the control strategies. It is even hard for a normal PID controller to get a stable performance in the whole working range. Some advanced control strategies are necessary for the system. As the mechanical system is decoupled, a single-input single-output(SISO) controller is enough for each direction of X and Y. For the decoupled system, the advantage is that the system can be modeled and measured in each direction separately. Since MRAC-PID controller owns the ability of great robust characteristics for nonlinear, hysteresis and variable parameters systems, it is adopted in this research to control the plant.

II. DESIGN AND MODELING OF THE DECOUPLED XY COMPLIANT STAGE

A. Design of The Decoupled XY Compliant Stage

As carefully studied in our previous work in [7], in order to construct a decoupled XY compliant stage, a mechanism emulated from rigid system with double four-bar parallelogram flexures is employed due to its simple structure and ease of manufacture. For a totally decoupled structure, one aspect is the kinematic decoupling, the other one is the force decoupling. The designed mechanical system is driven by electromagnetic actuators whose non-contact driven force can be used to cope with the function of force decoupling. The whole system can be shown in Fig.1. The mechanical structure is such simple that the entire mechanism system can be fabricated monolithically by wire electro-discharge machining (WEDM). Aluminium alloy material (AL7075-T651) with a high σ_y/E ratio is selected as the material to build the stage so that a large deflection is allowed. Associated with proper dimension, the motion range can

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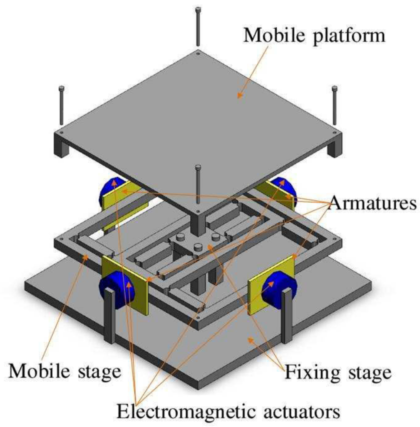

Fig. 1. 3D mechanical design of the manipulator

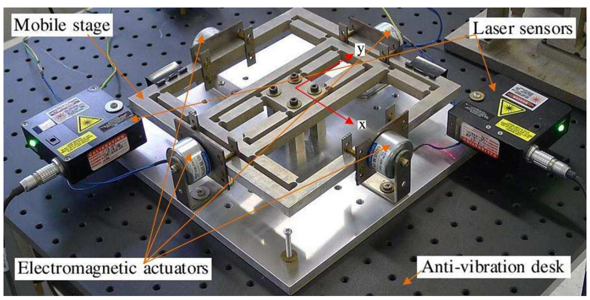

Fig. 2. Prototype of the mechanical system

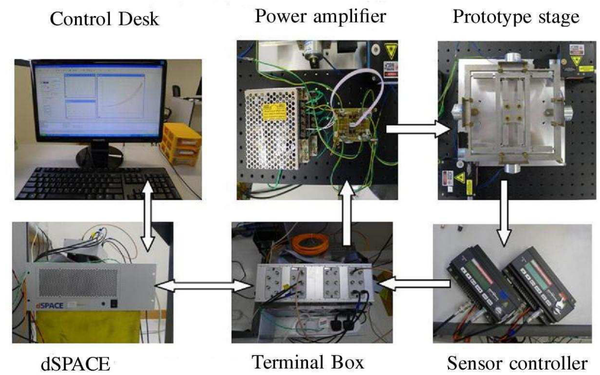

Fig. 3. Experimental setup and the connection diagram

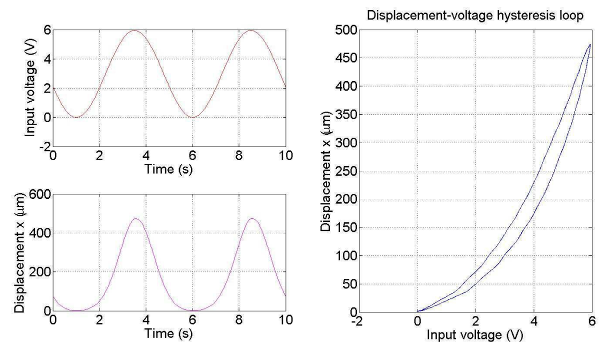

Fig. 4. Hysteresis loop in x direction

reach ±500 μm with ultrahigh precision which will have great demand in many micro/nano operations. After all, the advantage of this stage is that it is easily fabricated, low cost, with large working range and heavy load ability. If proper advanced control algorithms are adopted, high resolution will be realized.

III. Fabrication and Preliminary Experimental Study

After the mechanical structure is designed and the parameters are optimized, the prototype can be fabricated via electro-discharge machining. The prototype is shown in Fig.2. In the experimental study, two laser displacement sensors(Microtrak II head model: LTC-025-02 from MTI instrument,Inc.) with a resolution of 0.12μ and linearity better than 0.05% over a measurement range of $2mm$ associated with a dSPACE DS1005 (from dSPACE GmbH) rapid prototyping system equipped with DS2001 A/D and DS2102 D/A modular boards are employed to construct the experimental setup. The power amplifier for the electromagnetic actuators is made through OPA548 which is a low-cost, high-voltage/high-current operational amplifier. It is operated by either single(+8V to +60V) or dual power suppliers(4V to 30V), which outputs high current 3A continuously and 5A at peak. The connection scheme of the whole experimental system can be observed in Fig.3.

A. Open Loop Hysteresis Analysis

From the open loop control experiment, the hysteresis and the nonlinear characteristics of the system can be seen clearly. The maximum hysteresis rate can reach 11.5%. The nonlinear characteristics of the system can be seen from Fig.4, at the beginning, the first 2 voltages can just move the mobile stage 50 microns; the following 2 voltages from 2 to 4 volts can lead to 130 microns displacement; the last 2 volts can result in 300 microns. The slope is increasing according to the displacement of the mobile stage, in reality, it is related to the gap between the electromagnet and the armature. Therefore, how to model the electromagnetic actuators with variable gaps will be the key problems of the control system. Since the electromagnetic actuators are with fast responsibility, when the input signal is within 10Hz, the hysteresis loops look almost with no differences.

B. Preliminary PID Study

After the nonlinear features of the electromagnetic actuators are analyzed, the PID controller will be tested in the system as it is the most widely used controller. After the PID parameters are carefully tuned through engineering method, it can be seen from the Fig.5 that at the first step command from 0 to 100 μm, the response ascending so slowly indicates that the P gain of the PID parameters is obviously too small. But the following steps just used almost 4 seconds, 3seconds, and 2 seconds to reach the reference command which means the response is growing faster and faster when the armature

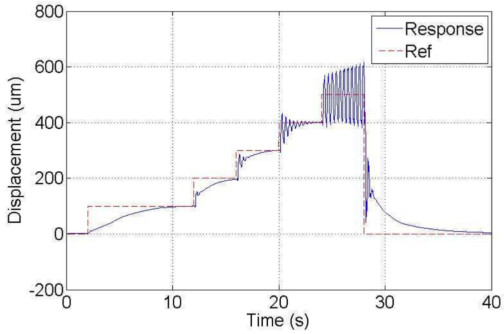

Fig. 5. Step response of preliminary PID control study

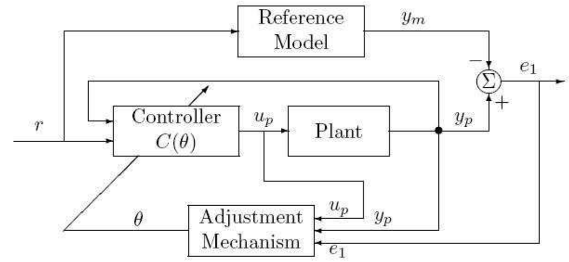

Fig. 6. General structure of a typical MRAC scheme

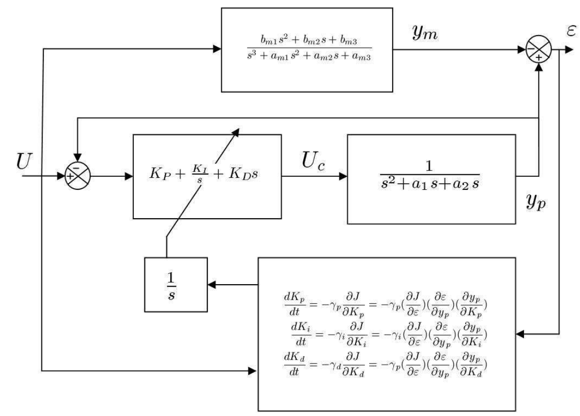

Fig. 7. MRAC PID controller block diagram for the electromagnetic actuated micro-positioning stage

is closer and closer to the electromagnet. The last step shows clearly that the parameters can not suit for the system so that the system is becoming oscillating and unstable for the long run. The experiment also shows clearly that the mechanical system with electromagnetic actuator is not a linear system. Since the driving force is not only determined by the voltage or current applied to the electromagnet but also by the distance between the armature and the electromagnet, the system is with serious nonlinear characteristics just as the preliminary PID experiment shows. It is impossible to obtain a satisfy robust performance at the whole working range by using normal PID controller. Further experiments show that even limited in a small displacement range, it is still very hard to obtain satisfy PID parameters because of the problems of overshoot and response time. For that reasons, an advanced controller should be adopted.

IV. Control Strategies

As indicated in preliminary study, we realize that the system is with typical nonlinear and hysteresis characteristics. Then, a more advanced controller should be adopted. Although in the model reference adaptive controller (M-RAC), the desired index of performance is given by the reference model, and the controller can establish robustness with respect to bounded disturbances and unmodeled dynamics, it is hard to adjust the parameters to obtain a good performance, even worse it is very difficult to make the system stable. From previous study, the PID controller can be used to control the designed micro-positioning stage in different working range with different PID parameters. That is to say, the parameters of the PID controller need to be adjusted on-line automatically. Many ways can be used to tune the PID parameters, aiming for combining the advantages of the MRAC and PID controller, the MRAC PID controller is adopted in this research. With the aid of MATLAB Simulink Toolbox and dSPACE system, the adopted MRAC PID controller is very easy to implement.

A. System Identification

Although the system is with nonlinearity and typical hysteresis characteristics, due to the great robust characteristics and the self adaptive ability of the MRAC PID controller, an approximated model of the system is needed for the design of the control system [9]. The approximated model can be obtained through many methods. An analytical model of the mechanical system with magnetic actuators was derived in [6]. In practice, the approximated model of the system can be obtained by system identification method conveniently.

Even if the system is with great nonlinearity and hysteresis feature, we can still use the system identification toolbox to obtain a approximated linearity auto-regression exogenous(ARX) model of the system through least-square(LS) method. In system model identification process, the most used model structure is the simple linear difference equation which relates the current output $y(t)$ to a finite number of past outputs $y(t-k)$ and inputs $u(t-k)$. The structure is thus entirely defined by the three integers na, nb, and n_k. n_a is equal to the number of poles and n_b is the number of zeros, while n_k is the pure time-delay (the dead-time) in the system. For a system under sampled-data control, typically n_k is equal to 1 if there is no dead-time. The orders n_a, n_b, and n_k can either be directly entered into the edit box orders in the parametric models window, or selected using the pop-up order menus in the editor. When selecting "Estimate", models corresponding to all of these structures are computed, a special plot window will then be opened that shows the fit of these models to validation data. There are two methods to estimate the coefficients a and b in the ARX model structure: least squares and instrumental variables methods. As the most known method, least square method is selected in this research, it can minimize the sum of squares of the right-

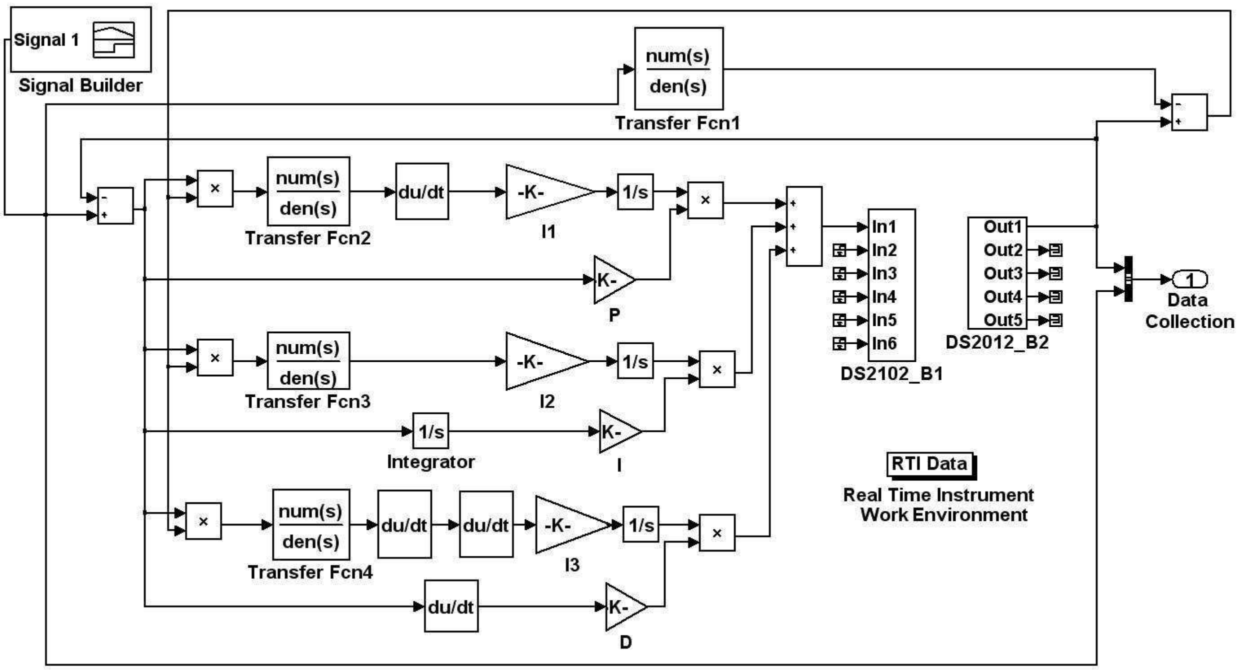

Fig. 8. The Simulink model for running under real-time work environment in dSPACE

hand side minus the left-hand side of the system differential expression, with respect to a and b. After the system is approximately identified, the system model can be used for the design of the MRAC PID controller.

B. MRAC PID Controller Design

The basic structure of a model reference adaptive control(MRAC) system is shown in the block diagram in Fig.6. The reference model is chosen to generate the desired trajectory for the plant output to follow. The tracking error represents the deviation of the plant output from the desired trajectory. According to the tracking error, output of the controller and the output of the plant, the adjustment mechanism automatically adjusts controller parameters so that the behavior of the closed-loop control plant output closely follows that of reference model. Structures of the reference model and the adaptive gains are chosen, which are based on the requirements of control performance.

The adjustment mechanism of MRAC system constructs by a popular method for computing the approximated sensitivity functions as so-called MIT rule. The algorithms for MIT rules can be derived by Tracking error:

$$e = y_p - y_m \tag{1}$$

Cost function:

$$J(\theta) = \frac{1}{2}e^2(\theta) \tag{2}$$

From the MIT rule, the change rate of θ is proportional to negative gradient of J as follows:

$$\frac{d\theta}{dt} = -\gamma\frac{\partial J}{\partial\theta} = -\gamma e\frac{\partial e}{\partial\theta} \tag{3}$$

where e denotes the model error and θ is the controller parameter vector. The components of $\frac{\partial e}{\partial\theta}$ are sensitivity derivatives of the error with respect to θ. The parameters γ is known as the adaption gain. The MIT rule is a gradient scheme that aims to minimize the squared model cost function.

According to the design process of the mechanism system of the positioning stage in [6], the system can be described by second order model $b/(s^2+a_1s+a_2)$. A block diagram of control system can be shown in Fig.7. Then, the closed loop transfer function can be derived as:

$$\frac{Y_p(s)}{U_c(s)} = \frac{b(K_ds^2+K_ps+K_i)}{s(s^2+a_1s+a_2)+b(K_ds^2+K_ps+K_i)} \tag{4}$$

Furthermore

$$\frac{Y_p(s)}{U_c(s)} = \frac{b(K_ds^2+K_ps+K_i)}{s^3+(a_1+bK_d)s^2+(a_2+bK_p)s+bK_i} \tag{5}$$

Consequently, the reference model can be chosen as the following form:

$$\frac{Y_m(s)}{U_m(s)} = \frac{b_{m1}s^2+b_{m2}s+b_{m3}}{s^3+a_{m1}s^2+a_{m2}s+a_{m3}} \tag{6}$$

According to the MIT rules, the parameters of PID controller K_p, K_i, and K_d can be determined by

$$\frac{dK_p}{dt} = -\gamma_p \frac{\partial J}{\partial K_p} = -\gamma_p (\frac{\partial J}{\partial \varepsilon})(\frac{\partial \varepsilon}{\partial y_p})(\frac{\partial y_p}{\partial K_p})$$
$$\frac{dK_i}{dt} = -\gamma_i \frac{\partial J}{\partial K_i} = -\gamma_i (\frac{\partial J}{\partial \varepsilon})(\frac{\partial \varepsilon}{\partial y_p})(\frac{\partial y_p}{\partial K_i}) \tag{7}$$
$$\frac{dK_d}{dt} = -\gamma_d \frac{\partial J}{\partial K_d} = -\gamma_p (\frac{\partial J}{\partial \varepsilon})(\frac{\partial \varepsilon}{\partial y_p})(\frac{\partial y_p}{\partial K_d})$$

where $\partial J/\partial \varepsilon = \varepsilon$, $\partial \varepsilon/\partial y = 1$, $\nabla = d/dt$

$$\frac{\partial y_p}{\partial K_p} = \frac{b\nabla}{\nabla^3 + (a_1 + bK_d)\nabla^2 + (a_2 + bK_p)\nabla + bK_i} \cdot [U_c - U_p] \tag{8}$$

$$\frac{\partial y_p}{\partial K_i} = \frac{b}{\nabla^3 + (a_1 + bK_d)\nabla^2 + (a_2 + bK_p)\nabla + bK_i} \cdot [U_c - U_p] \tag{9}$$

$$\frac{\partial y_p}{\partial K_d} = \frac{b\nabla^2}{\nabla^3 + (a_1 + bK_d)\nabla^2 + (a_2 + bK_p)\nabla + bK_i} \cdot [U_c - U_p] \tag{10}$$

Then, $\frac{\partial K_p}{\partial t}, \frac{\partial K_i}{\partial t}, \frac{\partial K_d}{\partial t}$ can be derived by

$$\frac{dK_p}{dt} = -\gamma_p \frac{\partial J}{\partial K_p}$$
$$= \gamma_p \varepsilon \frac{b\nabla}{\nabla^3 + (a_1 + bK_d)\nabla^2 + (a_2 + bK_p)\nabla + bK_i} \cdot [U_c - y_p] \tag{11}$$

$$\frac{dK_i}{dt} = -\gamma_i \frac{\partial J}{\partial K_p}$$
$$= \gamma_p \varepsilon \frac{b}{\nabla^3 + (a_1 + bK_d)\nabla^2 + (a_2 + bK_p)\nabla + bK_i} \cdot [U_c - y_p] \tag{12}$$

$$\frac{dK_d}{dt} = -\gamma_d \frac{\partial J}{\partial K_p}$$
$$= \gamma_p \varepsilon \frac{b\nabla^2}{\nabla^3 + (a_1 + bK_d)\nabla^2 + (a_2 + bK_p)\nabla + bK_i} \cdot [U_c - y_p] \tag{13}$$

A block diagram is shown in Fig.8, the model reference-based adaptive PID controller in Simulink will be compiled and downloaded into dSPACE for real time running.

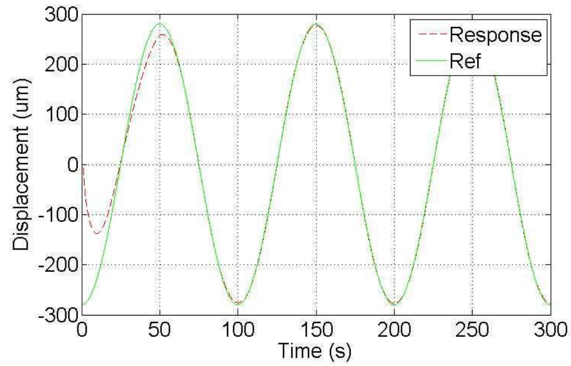

Fig. 9. Reference and response in x-direction when tracking a circle

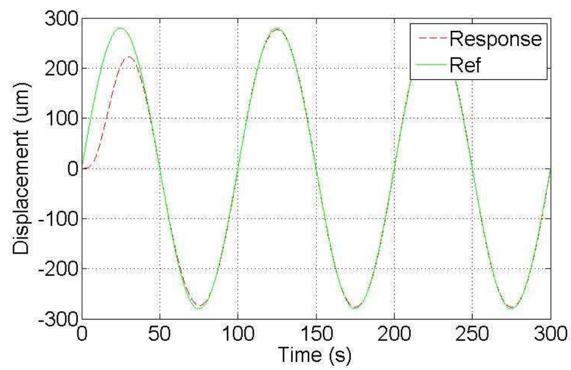

Fig. 10. Reference and response in y-direction when tracking a circle

V. EXPERIMENTS AND DISCUSSIONS

After the approximated model of the system is identified and the MRAC PID controller is built up in the MATLAB Simulink real-time workshop(RTW) environment, the Simulink model can be complied and downloaded into the dSPACE to run in realtime with the hardware in loop. The software Control Desk is used to supervise the experimental process and upload the experiment data instantaneously through optical fiber communication tool set.

In the experiment, two sinusoidal waves in two directions are used to drive the mobile stage to follow a circle, the learning and self adaptive time can be seen clearly from Fig.9 to Fig.10. It needs about 50s for the controller to learn and adapt the plant well. After the adaptive time, it can be seen that the mobile stage can track the given reference path exactly. It can be seen from Fig.11 and Fig.12, after 100s, the hysteresis problems are almost canceled, the response can track the reference signals well in both directions. The whole tracking performance can be seen in Fig.13. After the learning and adaptive period, the response follows the reference path exactly.

Compared with the previous simple PID control method, the MRAC-PID controller can tune the PID parameters automatically and make the system stable in the whole working range. But such a long learning and adaptive time may limit the application field of the designed positioning stage. This long time adaptive time may come from the approximated

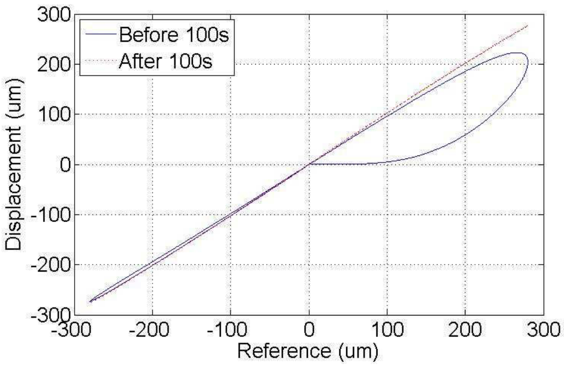

Fig. 11. Hysteresis performance in x-direction after applying the MRAC-PID controller on the stage

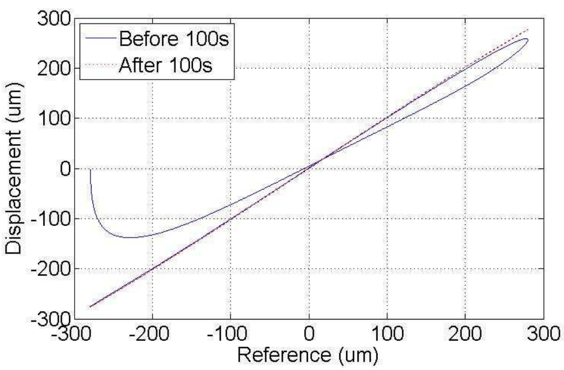

Fig. 12. Hysteresis performance in y-direction after applying the MRAC-PID controller on the stage

system model and the setting of adaptive gain. If more accurate model is used, or even associated with inverse hysteresis feed-forward compensator, and proper adaptive gains are selected, much better performance will be obtained.

VI. Conclusion

The paper presents the model reference adaptive control for a novel compliant flexures-based totally decoupled XY micro-positioning stage which is driven by electromagnetic actuators. The mechanical structure and the natural non-contact electromagnetic force can form a totally decoupled 2-DOF micro-positioning stage. Because the non-contact electromagnetic force is used, the mechanical structure can be very simple and can be fabricated in monolithic way by electric discharge machine. Moreover, due to the structure advantages, the designed manipulator can carry a heavy load. After the system is built up, preliminary experiment is carried out. It is found that the system is with very typical nonlinear and hysteresis features. A model reference adaptive PID controller is adopted in this research to caster for the nonlinear characteristics of the system. When the system is approximately identified, the MRAC PID controller is carefully designed according to the simple approximated model. The controller is built up in real-time work environment, which is complied and downloaded into dSPACE for running

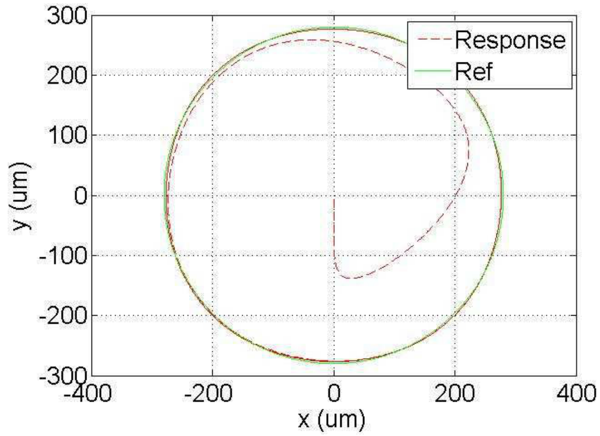

Fig. 13. Performance of the system when tracking a circle

in real time. Experimental results verify the process for a micro-positioning stage, the designed controller fulfills the expected performance. Although the controller tracks the reference well, the application field of this micro stage will be limited. Some other control strategies are still necessary to be studied and tried in this plant, grippers will be installed on the stage for performing some tasks based on our achieved research works [10] [11].

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