A Hybrid Fuzzy Robust control for Piezoelectric actuators

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Abstract: Piezoelectric actuators are used in a wide variety of precise Nano-positioning applications. Due to the effect of the nonlinear hysteresis, the positioning accuracy of the Piezoelectric actuators is limited. Hence, developing a high precise control scheme is considered a great challenge. It is desirable to take the effect of nonlinear hysteresis into consideration for enhancing the tracking positioning accuracy of the piezoelectric actuators. In this paper Robust µ-Synthesis and Hybrid Fuzzy Robust control schemes have been developed for a positioning system driven by Piezoelectric actuator. Simulation results show that the tracking error of both controllers was less than one nanometer. Moreover the Hybrid Fuzzy Robust Controller gives better tracking error than the Robust µ-Synthesis controller. The effectiveness of the proposed control schemes has been validated.

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1. Introduction

Recent advances in precision engineering and the concurrent development of advanced manufacturing techniques have the result that machined and manufactured components are no longer restricted to micrometer scale, but can now be fabricated at nanometer scale. The advanced technologies have given rise to an urgent requirement for the development of precise positioning systems capable of executing displacements with nano scale resolution (Basem *et al.,* 2010)

Piezoelectric (PZT) actuators are popularly applied as actuators in precision positioning systems due to its advantages of infinite displacement resolution, high speed, high bandwidth, high electrical–mechanical transformation efficiency, and little heat generation (Yung-Tien *et al.,* 2009).

The most commonly produced piezoelectric ceramics are lead-zirconate-titanate (PZT). Piezoelectric material is used to convert electrical energy to mechanical energy and vice-versa. Piezoelectric sensors are used in a variety of applications to convert mechanical energy to electrical energy such as: pressure-sensing applications, detecting imbalances of rotating machine parts, ultrasonic level measurement, flow rate measurement, sound transmitters (buzzers), sound receivers (microphones), …etc. However, piezoelectric actuators convert electrical energy to mechanical energy, and are used in many applications such as: scanning microscopy, patch clamp, gene manipulation, vibration cancellation, R/W head testing, hydraulic valves, drilling equipment, diamond turning machines …etc.

PZT actuators have many advantages such as (Reza Moheimani *et al.,* 2006 and Peng , 2008)

- Piezoelectric actuators have excellent resolution in displacement, high stiffness, high electrical mechanical coupling efficiency, small size, small heat expansion, low power consumption and fast response.
- The piezoelectric actuators make motion in micrometer range with sub-nanometer precision.
- There are no moving parts in contact with each other to limit the resolution.
- The piezoelectric actuators capable of moving loads of several tons and cover travel ranges of several (100 µm) with resolutions in the sub-nanometer range (physikinstrumente.com).
- The piezoelectric actuators behave pure capacitive load, so they consumes virtually no power.
- The piezoelectric actuators do not produce magnetic field nor are they affected by them.

Since piezoelectric materials are ferroelectric, they are fundamentally non-linear in their response to an applied electric field, exhibiting a hysteresis effect between the electric field and the displacement (Changhai *et al.,* 2006).

Hysteresis nonlinearities can be classified into two categories (Mayergoyz *et al.,* 1991):

- Nonlinearities with local memory where the future output depends only upon the future input and the present output,
- Nonlinearities with nonlocal memory where the future output depends not only upon the current output and the future input but also on the past extreme values of the input. This type of effect can be observed in magnetic and piezoelectric materials and also in friction.

The hysteresis is not a differentiable but is a nonlinearity with local memory, so that it causes positioning errors which critically limit the operating speed and precision of Piezoelectric actuators (Chih-Jer *et al.,* 2006). Nonlinear hysteresis effects can be corrected using charge control however; it may lead to drift and saturation problems as well as reduce the operating range greatly (Chih-Jer *et al.,* 2006).

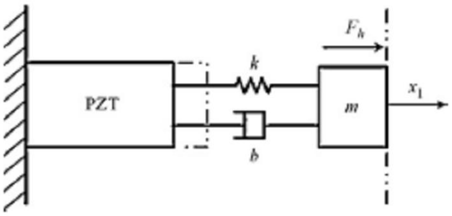

Fig. 1 The schematic diagram of precision moving stage using PZT actuator.

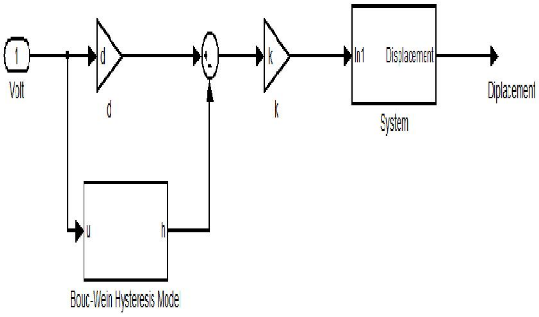

Fig. 2 The block diagram of the moving stage.

Therefore, appropriate closed-loop control methodologies have been established to achieve the desired positioning accuracy of the piezoelectric systems.

2. Piezo Positioning system:

In this paper a moving stage driven by a PZT actuator is constructed so that one end of the PZT actuator is fixed to the wall and the other end is connected to the moving stage sliding on the horizontal surface. If the frictional force is very small compared to the generating force of the PZT actuator, the physical model of the moving stage system can be depicted in Fig.1 (Yung-Tien *et al.,* 2009). Applying an input voltage to the PZT actuator, an elongation is produced and then results in a force F_h acting on the imaginary wall.

$$m\ddot{x}_1 + b\dot{x}_1 + kx_1 = F_h = k(d_e u - h) \qquad (1)$$

Where *m* is the equivalent mass of the PZT actuator and the moving stage, *b* is the equivalent damping coefficient, *k* is the equivalent spring coefficient, *u* is the input voltage, which is applied to the PZT actuator to drive the stage, *x*1 is the displacement of the stage, *de* is the effective piezoelectric coefficient of the PZT actuator, and *h* is a variable used for describing the hysteresis effect, respectively.

In this paper, the Bouc–Wen model is used to describe the hysteresis behavior in the piezoelectric actuator. For the Bouc–Wen model, when the material is uniform elastic, the state variable *h* forms the hysteresis nonlinear dynamics Therefore, based on the Bouc–Wen model (Chen *et al.,* 1999), the dynamical equation is represented in the following form:

$$\dot{h} = \alpha d_e \dot{u} - \beta|\dot{u}|h - \gamma\dot{u}|h| \quad (2)$$

Where α, β, and γ are the parameters adjusting the shapes of the hysteresis loop. Therefore, the block diagram of the moving stage system can be illustrated in Fig. 2.

The identified parameters are given in Table1 (Chih-Jer *et al.,* 2006)

TABLE 1: Estimated parameters for the PZT moving stage model.

m	0.148 Kg	α	0.385
b	129.5 Ns/m	β	0.0235
K	$2.95\text{x}10^6$ N/m	γ	0.0495
d_e	$1.59\text{x}10^{-8}$		

The open loop response of PZT actuator in order to confirm the validity of system parameters, sinusoidal input with amplitude 100V is applied. Fig. 3 shows the hysteresis loop and nonlinearity in the displacement of PZT actuator.

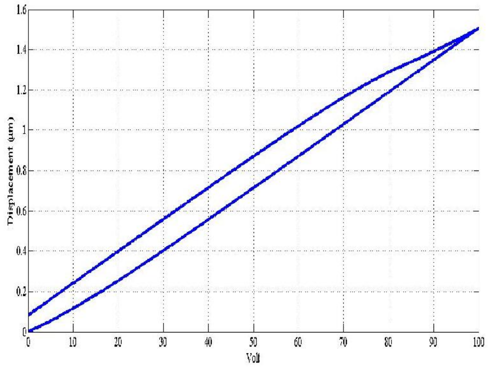

Fig. 3 Simulation Hysteresis Loop.

3. Robust µ-Synthesis Controller

In this section, a µ-Synthesis controller will be developed for compensating the nonlinearities effect in the PZT actuator due to the hysteresis in order to reach a precise and accurate output.

The µ-Synthesis framework requires two conditions:

- First Reformulating the plant to be MIMO system.

- The inputs and outputs to be normalized.

From Fig. 4 it can be seen that the plant is MIMO where the inputs are :

- Volt which is the control action.
- Xref which is the reference displacement required for the system to track.

While the outputs will be Z1, Z2 and the e (error) the difference between Xref and the actual displacement from the system.

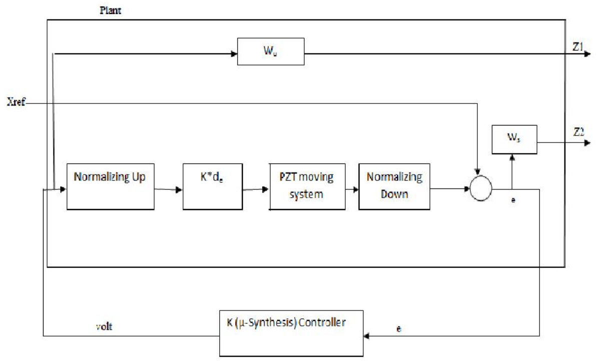

Figure. 4 μ-Synthesis framework of the PZT moving system.

The block Normalize up is a weighting function to normalize the volt which is the output from the controller and input to the system to be continuous, while the block normalize down is a weighting function to normalize down the actual output displacement from the system.

More weighting function W_U and W_S are added to penalize the control action and the tracking error respectively.

It should be noticed that this configuration is used for synthesizing the controller, K. Once the controller is obtained it is inserted in the usual SISO configuration.

To define this plant on MATLAB, it needs to be on the form of system matrix which is an augmentation of the state space matrices into one partitioned matrix (Zhou *et al.,* 1999) as shown in Fig. 5. The signal w is the reference and/or disturbance inputs, z is the penalized performance indices, u is the control action, and y is the feedback measurement (Madden et al., 2009). This is done on MATLAB by one of the two commands (Balas *et al.,* 2012):

P=pck(A, [B1 B2], [C1; C2], [D11 D12; D21 D22]);

P=sysic

The robust control is the art of selecting weighting function W_u and W_s. The widely used weighting function W_s is given by (Skogestad *et al.,* 2001):

$$W_s = \frac{s/_M + \omega_o}{s + \omega_o A}$$

MATLAB introduces the function dksyn, which computes the μ-Synthesis controller based on DK-iteration (Balas *et al.,* 2012).

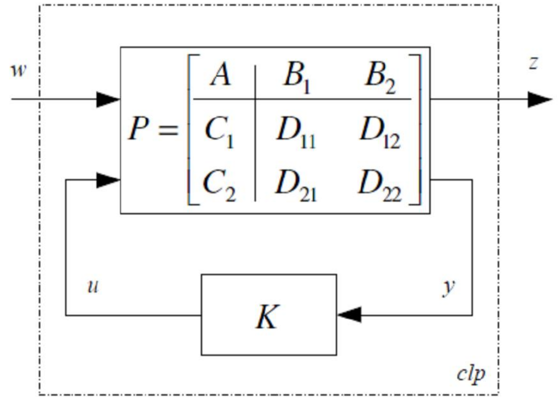

Fig. 5 General Form of Robust control problem (Madden et al., 2009).

4. Hybrid Fuzzy Robust Control

In this section a hybrid Fuzzy Robust Control is developed in order to enhance the performance of the PZT actuator and compare its simulation results against Robust μ-Synthesis Control.

The developed Fuzzy logic controller will be used to compensate the error difference between the Xref and the control action produced from Robust μ-Synthesis Control since that the control action and the reference input are normalized value and the difference between them should be at the least till vanishing, so the difference between them will be the input to the Fuzzy logic controller and the output will be added to the control action from the Robust μ-Synthesis control and the result will be the applied voltage to PZT actuator as shown in Fig.6.

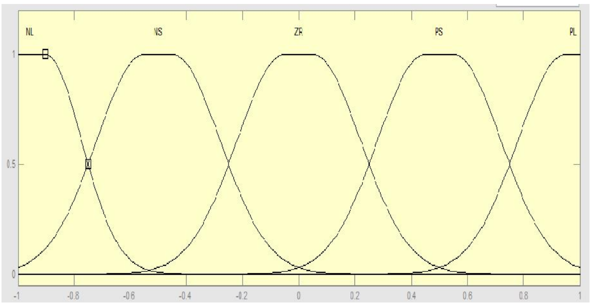

Fig.6 Block diagram of Hybrid Fuzzy Robust Control for PZT moving system.

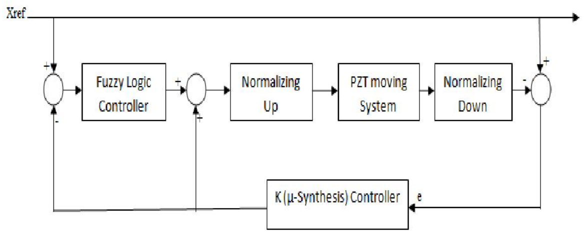

Fig.7 Inputs/Outputs Membership function.

The first fuzzy control application was developed by Mamdani and his research group. The fuzzy control is based on the development of fuzzy logic, as in 1965, Zadeh wrote a paper in which he introduced fuzzy sets, that are with unsharp boundaries and are generally in better agreement with the human mind that work with shades of gray, rather than with just black or white (Basem *et al.,* 2010). The fuzzy control is to be designed to automate how a human expert who is successful at this task would control the system. The expert tells us (the designers of the fuzzy logic control) what information will be used as inputs to the decision-making process. Although, the error and its derivatives are chosen as inputs for the controller, as this choice makes good intuitive sense (Kevin et *al.,* 1998; Ali et *al.,* 2001).

Fuzzy control has met a growing interest in many control applications due to its advantages (Basem *et al.,* 2010):

1- It does not need any exact system's mathematical model.

2- It can handle nonlinearity of arbitrary complexity.

3- It is based on the linguistic rules with an IF–THEN general structure.

Fuzzy logic control is done through three phases

a. Fuzzification:

The fuzzy control initially will convert its normalizedinput from a crisp value linguistic values. The membership functions are selected a gaussian shape that's because the system requires smooth transitions, which the trapezoids and the triangular do not have.

Gaussian shape can guarantee that most of the common input that enter the fuzzy logic controller. The input and output Membership functions are defined within the range [-1,1] as the input and output are normalized, and will have the following labels: NL (Negative Large), NS (Negative Small), ZR (Zero), PS (Positive Small), PL (Positive Large) as shown in Fig.7.

b. Rule Base

The mapping of the fuzzy linguistic inputs into the required linguistic output is done by the rule base. Any rule in the fuzzy control consists of antecedent, which is the IF part, and consequent, which is the THEN part. In this paper the inference engine is Mamdani strategy with five if-then rules.

c. Defuzzification

In order to convert the output from the Fuzzy controller which is in the fuzzy form into a crisp value a commonly defuzzification technique called Centroid is used in this paper.

5. Simulations and Results

In this section Computer Simulations are done to show the performance of both the Robust μ-Synthesis Controller and the Hybrid Fuzzy Robust Controller. In addition, a traditional PI controller will be also simulated in order to illustrate the effectiveness of the proposed Hybrid Fuzzy Robust controller.

5.1 Using the Robust μ-Synthesis Controller

Before starting with simulation the weights in equation and W_u must be selected as in Table 2, for synthesizing the controller.

TABLE 2Weight values for Robust μ-Synthesis control

M	1.5
ωo	10^6
A	10^{-7}
W_u	1.511

The controller produced is inserted into the SIMULINK model as shown in Fig.8 as a discrete state space block.

By applying a sinusoidal waveform as a reference (X_{ref}) with amplitude value 1 which is normalized, i.e. it corresponds to 1.5 μm.

All simulation results are shown in Figs. 9-11. Figs.9a, 9b show that the system output X_{act} follows the reference signal X_{ref} satisfactorily. Although nonlinear hysteresis acts on the moving stage system,

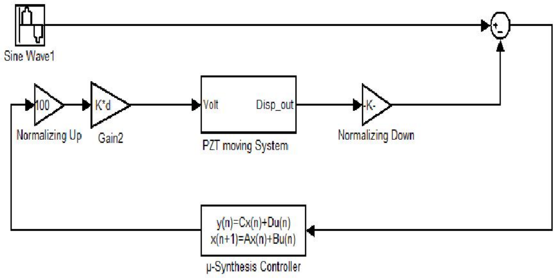

Fig.8 Simulink model to simulate the position μ-Synthesized controller.

It can be observed from Fig.10 that the tracking error is small ranging from -0.53208 to 0.53208 nm. The only concern that there is some fluctuations are observed with maximum tracking error around 1 nm.

The hysteresis nonlinearity effect and the relation between the input voltage and the displacement is almost linear as shown ion Fig.11.

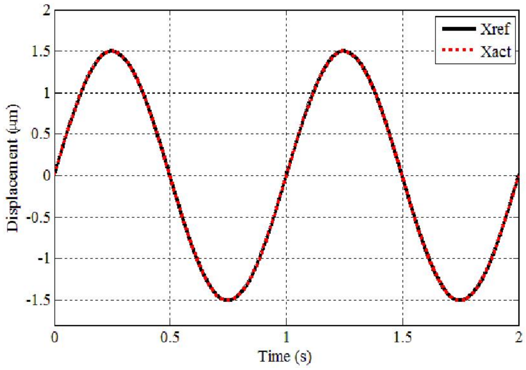

Fig. 9a Time response of normalized system output and reference input of Robust µ-Synthesis control.

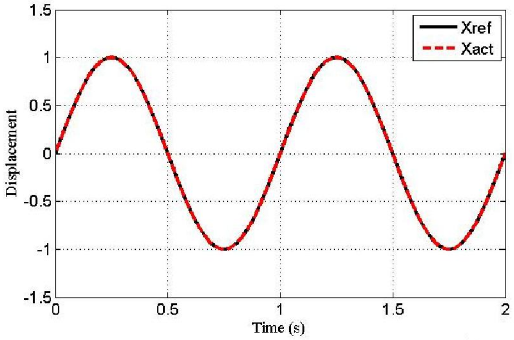

Fig.9b Time Response of system output and reference input of Robust µ-Synthesis control.

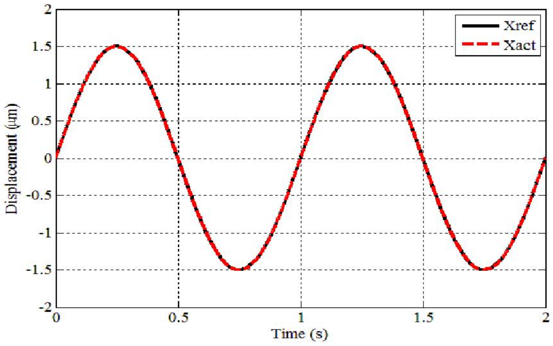

Fig.10 Tracking error of Robust µ-Synthesis Control.

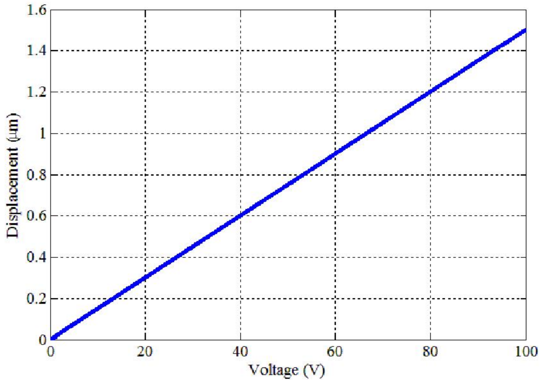

Fig.11 Hysteresis charcteristics using Robust µ-Synthesis Control.

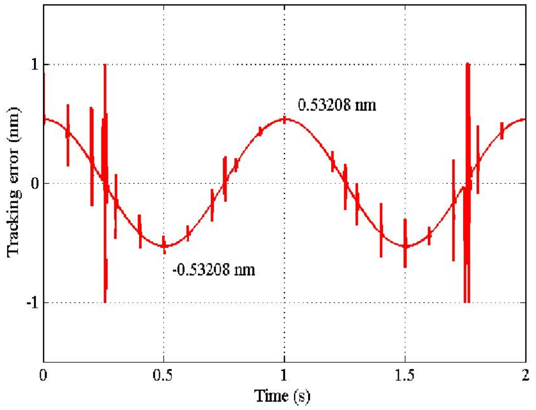

Fig.12a Time response of normalized system output and reference input of Hybrid Fuzzy Robust control.

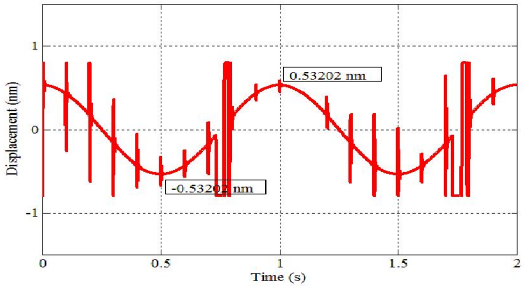

Fig. 12b Time response of system output and reference input of Hybrid Fuzzy Robust control.

5.2 Using the Hybrid Fuzzy Robust Controller

By using the same parameters and conditions as simulated in Section 5.1 and by applying the proposed Hybrid Fuzzy Robust Control. All the simulation results are shown in Figs.12-14Figs. 12a, 12b show that the system output X_{act} also follows the reference input signal X_{ref}, another main point is that the tracking error is less than the Robust µ-Synthesis Controller, also the fluctuations amplitude decreased with maximum tracking error around 0.8 nm as shown in Fig.13. Fig.14 shows that the relation between the input voltage to the system and the output displacement is linear.

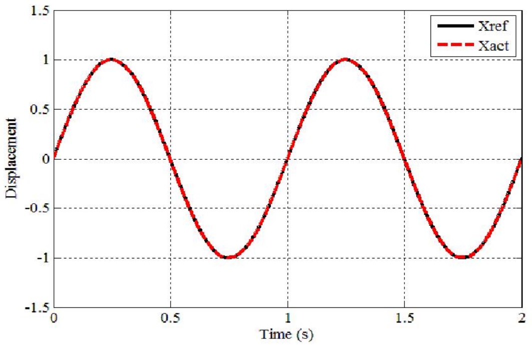

Fig.13 Tracking error of Hybrid Fuzzy Robust control.

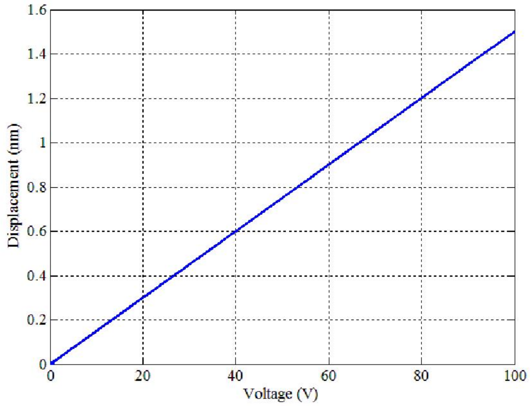

Fig. 14 Hysteresis characteristics using Hybrid Fuzzy Robust controller.

5.3 Using normal PID controller

The simulation results using K_p=953218594, K_i=40368336210 and K_d=172738 are shown in Figs. 15-17.

From Fig.15 it is observed that the system output X_{act} can also follow the reference signal X_{ref} . It is clear from Fig.16 that the tracking error behaves as a periodic fluctuation ranging from -14.53 nm to 14.53 nm. The control input is shown in Fig.17, it is observed that at the peak points there are fluctuations which is considered to be non smooth control action.

6. Conclusion:

The main aim from this paper is to develop a Hybrid Fuzzy Robust Control in order to eliminate the hysteresis non linearity effect and enhance the performance of the system according to simulation results the proposed Fuzzy Robust controller was verified as effective, and the tracking error was less than 1 nanometer. The Robust µ-Synthesis controller is also effective but with higher tracking error than the Fuzzy Robust Control and higher fluctuations.

The PID controller has the highest tracking error compared to the other two controllers and has a limited performance as the model is nonlinear. The proposed Fuzzy Robust Controller can be effectively applied to high positioning devices using PZT actuators to obtain high precision performance.

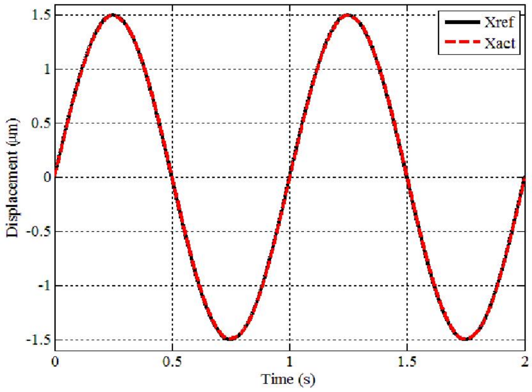

Fig. 15 Time response of system output and reference input of PI control.

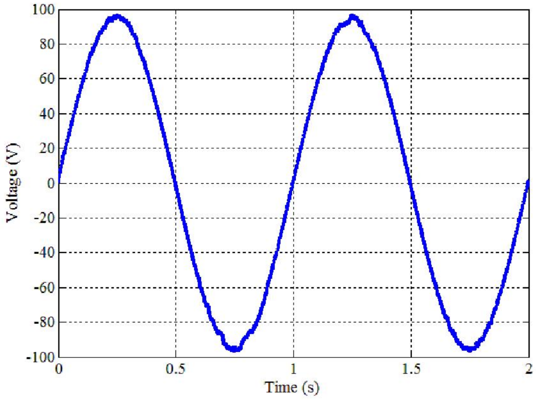

Fig. 16 Tracking error of PI control.

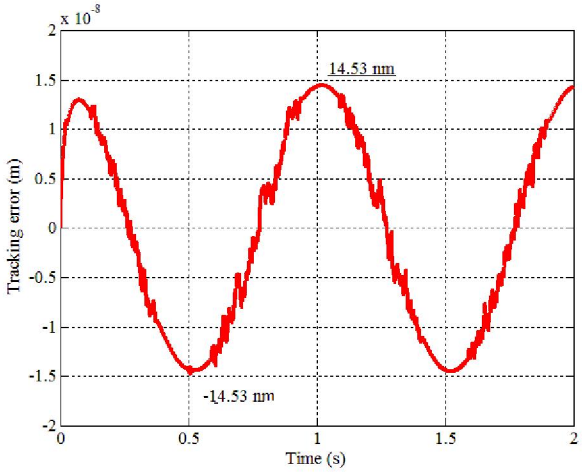

Fig.17 Control input of PI control.

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