# 백스테핑제어기를 이용한 전기유압액추에이터의 위치제어
# Position control of Electro hydrostatic actuator (EHA) using a modified back stepping controller

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**Abstract**: Nowadays, electro hydrostatic actuator (EHA) has shown great advantages over the conventional hydraulic actuators with valve control system. This paper presents a position control for an EHA using a modified back stepping controller. The controller is designed by combining a backstepping technique and adaptation laws via special Lyapunov functions. The control signal consists of an adaptive control signal to compensate for the nonlinearities and a simple robust structure to deal with a bounded disturbance. Experiments are carried out to investigate the effectiveness of the proposed controller.

## NOMENCLATURE

| | |
|---|---|
| $V_1, V_2$ | : checkvalves |
| $V_3, V_4$ | : reliefvalves |
| $m$ | : equivalent mass |
| $k$ | : equivalent stiffness |
| $c$ | : equivalent damping |
| $P_H, P_R$ | : pressure in each chambers |
| $A_H, A_R$ | : actuating areas |
| $F$ | : external loading force. |
| $C_t$ | : coefficient of the internal leakage |
| $\beta_e$ | : effective bulk modulus |
| $B_{01}, B_{02}$ | : Initial volumes of each chambers |
| $Q_H, Q_R$ | : flow rate to the chamber H and R |
| $Q_{pump}$ | : flow rate of the pump |
| $k_{leakage}$ | : leakage constant |
| $D$ | : pump displacement |
| $Q_{v1}, Q_{v2}, Q_{v3}, Q_{v4}$ | : flowrate of $V_1, V_2, V_3, V_4$ |
| $x$ | : state vector of the system |
| $\omega$ | : speed command for the AC servo motor |
| $x_{d1}$ | : desired trajectory |
| $z_1$ | : tracking error. |

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## 1. Introduction

Hydraulic systems have been widely used in industrial applications because of their durability, high power-to-weight ratio, reliability and large force and torque, etc. However, most conventional hydraulic actuators consist of valve control system which is the main cause of the low energy efficiency. The loss of energy is due to the leakage from the pump bypass valves or transfer of energy into heat via throttle losses at the control valves. Consequently, several techniques have been developed to overcome this challenge and also to satisfy the demands in hydraulic engineering[1-3].

Recently, the concept of Electro Hydrostatic Actuator (EHA) has been introduced by engineers at Moog, Inc. (East Aurora, NY).Schematic of the EHA is shown in figure 1. Here, the position of hydraulic cylinder is adjusted directly by the

operation of the bi‑directional pump. Obviously, the EHA acts as a Power –Shift which shifts the power from high‑speed electric motor to the high‑force of hydraulic cylinder. Thus, the EHA creates a sleeker, cleaner way to produce hydraulic power with higher energy efficiency, as proven by Rahmfeld and Ivantysynova[4]. Because of its advantage, the EHA has been developed as commercial produces, e.g., the mini motion package from Kayaba Industry Co.[5], or the intelligent hydraulic servo drive pack from Yuken Kogyo Co.[6].

Contrary to the advantages of simple structure and good efficiency, the control of EHA is very complicated due to the nonlinearity and the large uncertainties of hydraulic systems. The nonlinearities originate from dynamics of piston pump and the actuating cylinder while the uncertainties is due to the unstableness of hydraulic parameters such as bulk modulus, compressibility and viscosity of oil, etc. Since the EHA possesses dead‑zone when the pump changes direction, the control problem of EHA becomes even more challenging.

In literatures, the control of hydraulic valve –cylinder system has been studied for years. To deal with nonlinearity and uncertainty problems, the adaptive sliding mode[7], and the adaptive backstepping[8] algorithms have been adopted. However, the use of these techniques for the position control of EHA is surprisingly rare.

The position control of EHA has been introduced by Ahn et al.[9] using Quantitative Feedback Theory (QFT). The controller design starts with experimental analysis on frequency response of EHA. Then, the controller is calculated for EHA to satisfy the control criteria for step response. Although the QFT control provides sufficient results in position control of EHA, the development of other control technique for EHA is an interesting topic.

This paper presents a position control of an EHA system using adaptive sliding mode technique. Firstly, the dynamic model of EHA is investigated. Then, the position control using backstepping technique with adaptive rules is developed. The control signal consists of an adaptive control signal to compensate nonlinearities and a simple robust structure to deal with the bounded disturbance. Finally, experimental results are carried out to evaluate the effectiveness of the proposed control method.

The remainder of this paper is organized as follows. In Section 2, the mathematical model of the EHA is described. Then, the position controller is designed in Section 3, while experimental results are carried out in Section 4. Finally, Section 5 gives some conclusions.
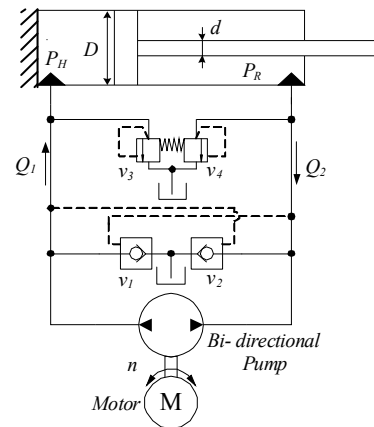


Fig. 1 Electro‑Hydrostatic Actuator

## 2. Modeling of EHA system

### 2.1. Experimental apparatus

Schematic diagram of the whole system which is consideration subject in this work is shown as Fig. 2. The system consists of a PC based control system, sensing system, and two electro –hydrostatic actuators (EHA), which serve as motion generator (main EHA) and load simulator (load generator). In this configuration, the movement of main cylinder is adjusted by the speed of an AC servo motor (SGDM‑50ADA) through a fixed displacement piston pump, reservoir and hydraulic control circuit. One linear encoder, two pressure transducers and one load
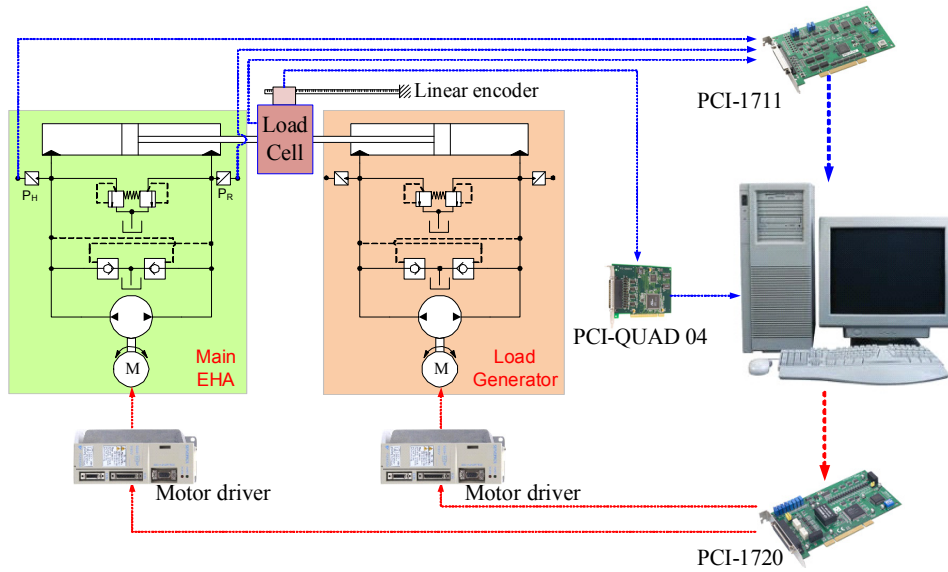
Fig. 2 System schematic Diagram

cell are installed to the system to measure the cylinder position, the pressure of two chambers of the main EHA and the loading force, respectively. One encoder, Quad – 04 card by Measure Computing Corp., and two multi-function data acquisition cards, A/D 1711 and D/A 1720 by Advantech, are installed on the PCI slots of the PC to perform the peripheral interfaces. In order to evaluate the main EHA system for variant working conditions, the load simulator is installed. Generated load to the main cylinder is adjusted via force control applied to the load generator.

For the position control task, the processing system is built on a personal computer (Intel ® CoreTM2 Duo 1.8 GHz) within Simulink environment combined with Real-time Windows Target Toolbox of MATLAB. This processing system calculates the control signal based on the feedback states e.g., cylinder position, pressure of two chambers of main EHA, and loading force on main cylinder to adjust the position of the main cylinder. Control signal is in the form of analog voltage signal which is sent to the main EHA driver from PC through the 1720 D/A converter. Meanwhile, the position information from the linear encoder is captured through interface of the PCI Quad – 04. Other data from load cell and two pressure transducers are sent back to the PC

through the 1711 A/D converter. Setting parameters for the EHA system are shown in Table 1.

## 2.2. Mathematical model

Consider EHA system (as shown in Fig. 3), the dynamics of the piston can be described by:

$$m\ddot{y} = P_H A_H - P_R A_R - F \tag{1}$$

where, $m, k, c$ is the equivalent mass, stiffness and damping, respectively; $y$ is system displacement; $P_H$, $P_R$ are pressure in two chambers respectively; $A_H$, $A_R$ are actuating areas respectively; and $F$ is external loading force.

Assuming there is no external leakage, the dynamics of cylinder oil flow can be written as:

$$\begin{cases} \dot{P}_H = \dfrac{\beta_e}{V_{01} + A_H y}\left(Q_H - A_H \dot{y} - C_t\left(P_H - P_R\right)\right) \\ \dot{P}_R = \dfrac{\beta_e}{V_{02} - A_R y}\left(Q_R + A_R \dot{y} + C_t\left(P_H - P_R\right)\right) \end{cases} \tag{2}$$

Where: $C_t$ is the coefficient of the internal leakage of the cylinder, $\beta_e$ is the effective bulk modulus of the hydraulic fluid in the container, $V_{01}$, $V_{02}$ are the original total control volumes of the two chambers respectively (including the volume of pipelines and initial cylinder chambers), $Q_H$

represents the supply flow rate to the H chamber (or cylinder end), and $Q_R$ represents the supply flow rate to the R chamber (or rod-end).

Table 1: Setting parameters for EHA system.

| System Components | Parameters | Specification |
|---|---|---|
| Hydraulic Pump | Displacement | 16 [cc/rev] |
| | Rate rotation speed | 1500 [rpm] |
| | Relief pressure | 60 [bar] |
| Hydraulic Cylinder | Tube diameter - D | 63 [mm] |
| | Rod diameter - d | 35 [mm] |
| | Length of stroke | 310 [mm] |
| | Maximum pressure | 70 [bar] |
| Hydraulic oil | Effective bulk modulus | $1.5 \times 10^9$ [Pa] |
| | Specific gravity | 0.87 |
| Linear Encoder | Model | MHG-TT |
| | Full range | 330 [mm] |
| | Resolution | 10 [] |
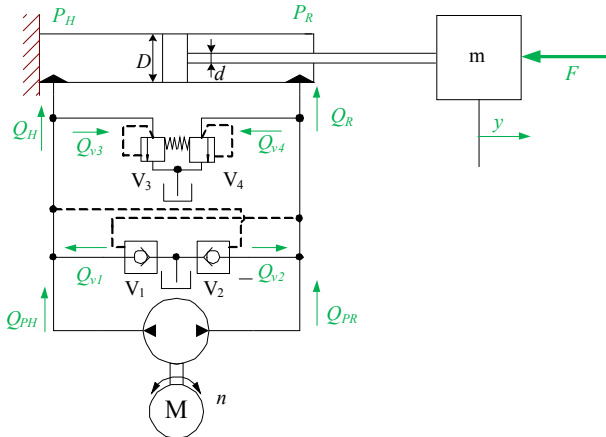


Fig. 3 EHA system with load

Flow rates into two chambers are calculated as:

$$\begin{cases} Q_H = Q_{PH} + Q_{v1} - Q_{v3} \\ Q_R = Q_{PR} + Q_{v2} - Q_{v4} \end{cases} \quad (3)$$

where $Q_{PH} = -Q_{PR} = Q_{pump}$ is the supplying flow rate from the pump:

$$Q_{pump} = D\omega - k_{leakage}(P_H - P_R) \quad (4)$$

where, $k_{leakage}$ is the leakage constant, $D$ is displacement of the pump, and $\omega$ is the input

driven speed from the servo system.

## 2.3 Control problem statement

In normal operation, the system pressure values: $P_H, P_R$ should be kept under the setting value $P_{set}$ of two relief valves V$_3$ and V$_4$. It means that the flowrates through the two relief valves $Q_{v3}$, $Q_{v4}$ are zero. Consequently, equation (3) can be rewritten as:

$$\begin{cases} Q_H = Q_{PH} + Q_{v1} \\ Q_R = Q_{PR} + Q_{v2} \end{cases} \quad (5)$$

Define the state vector as

$$x = (x_1, x_2, x_3, x_4,)^T \equiv (y, \dot{y}, P_H, P_R,)^T,$$

The simplified mathematical model of EHA system can be described by employing (1-4):

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = \frac{1}{m}(A_H x_3 - A_R x_4) - \frac{F}{m}$$
$$\dot{x}_3 = \frac{\beta_e}{V_{01} + A_H x_1}\Big( D\omega - (k_{leakage} + C_t)(x_3 - x_4) + $$
$$\quad - Q_{v1} - A_H x_2 \Big)$$
$$\dot{x}_4 = \frac{\beta_e}{V_{02} - A_R x_1}\Big( -D\omega - (k_{leakage} + C_t)(x_4 - x_3) + $$
$$\quad - Q_{v2} + A_R x_2 \Big) \quad (6)$$

Let $x_{34} = \dfrac{A_H x_3 - A_R x_4}{m}$, $d = -\dfrac{F}{m}$, $k_{leak} = k_{leakage} + C_t$,

$\beta_1 = \dfrac{A_H \beta_e}{m}$, $\beta_2 = \dfrac{A_R \beta_e}{m}$, and $k_{eq} = \sqrt{\dfrac{2}{\rho}} C_d$, the state space can be rewritten in strictly feedback form as:

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = x_{34} + d$$
$$\dot{x}_{34} = \left( \frac{\beta_1}{V_{01} + A_H x_1} + \frac{\beta_2}{V_{02} + A_R x_1} \right) D\omega + $$
$$\quad + \left( \frac{\beta_1}{V_{01} + A_H x_1}(-Q_{v1} - k_{leak}(x_3 - x_4) - A_H x2) + \right.$$
$$\quad \left. - \frac{\beta_2}{V_{01} - A_R x_1}(-Q_{v2} + k_{leak}(x_3 - x_4) + A_R x_2) \right) \quad (7)$$

Obviously, the system states are adjusted by the

speed of the bi‑directional pump which is driven by an AC servo motor. Given a bounded desired trajectory $x_{d1}$, the objective of this paper is to determine the input speed command for the AC servo motor $\omega$ to control the output position $x_1$ track as closed as possible to $x_{d1}$.

## 3. Control design

In this section, the position control is developed basedon adaptive backstepping technique. The backstepping controller is constructed to find out the input speed command $\omega$ as follows.

**Step 1.** Define the tracking error as:

$$z_1 = x_1 - x_{d1}$$

The derivative of tracking error is as follows:

$$\dot{z}_1 = x_2 - \dot{x}_{d1} \tag{8}$$

Let

$$\begin{cases} x_{2d} = \dot{x}_{1d} - k_1 z_1 \quad, \ k_1 > 1 \\ z_2 = x_2 - x_{2d} \end{cases}$$

It follows that

$$z_2 = \dot{z}_1 + k_1 z_1 \tag{9}$$

Here, if $z_2 \to 0$, then $z_1 \to 0$. Thus, the next step is to control $z_2$ as small as possible.

**Step 2.** Note that

$$\dot{z}_2 = \dot{x}_2 - \dot{x}_{d2} = x_{34} + d - \ddot{x}_{1d} + k_1 \dot{z}_1$$

Let

$$\begin{cases} x_{34d} = \ddot{x}_{1d} - k_1 \dot{z}_1 - k_2 z_2 \quad, \ k_2 = \dfrac{1+D}{\delta} \\ z_{34} = x_{34} - x_{34d} + d \end{cases}$$

where, $D = \sup|d|$, and $\delta$ is the acceptable boundary of error $z_2$.

Then

$$z_{34} = \dot{z}_2 + k_2 z_2 + d \tag{10}$$

Obviously, if we can control the error $z_{34}$ at small value, then the error $z_2$ is bounded around $\delta$. Hence, next step is to control the error $z_{34}$ as

small as possible.

**Step 3.** This step aims to synthesize an actual control law for the input $\omega$ of the system. Rewrite the last equation of (7) as

$$\dot{x}_{34} = \frac{h_1(x)\omega + h_2(x)}{g(x)} \tag{11}$$

where

$$g(x) = (V_{01} + A_H x_1)(V_{02} - A_R x_1)$$
$$= V_{01}V_{02} + (V_{02}A_H - V_{01}A_R)x_1 - A_H A_R x_1^2 \geq 0$$

$$h_1(x) = (\beta V_{02} + k_A \beta V_{01})D$$

$$h_2(x) = (\beta V_{02} - \beta A_R x_1)(-Q_{v1} - k_{leak}(x_3 - x_4) - A_H x2)$$
$$\quad - (k_A \beta V_{01} + k_A \beta A_H x_1)(-Q_{v2} + k_{leak}(x_3 - x_4) + A_R x_2)$$
$$= -(k_{leak}k_A \beta V_{01} + k_{leak}\beta V_{02})(x_3 - x_4)$$
$$\quad - (A_R k_A \beta V_{01} + A_H \beta V_{02})x_2 + (Q_{v1}\beta A_R + Q_{v2}k_A \beta A_H)x_1$$
$$\quad + (k_{leak}\beta A_R - k_{leak}k_A \beta A_H)x_1(x_3 - x_4)$$
$$\quad + (\beta A_R A_H - k_A \beta A_H A_R)x_1 x_2 + (-Q_{v1}\beta V_{02} + Q_{v2}k_A \beta V_{01})$$
$$= -(k_{leak}k_A \beta V_{01} + k_{leak}\beta V_{02})(x_3 - x_4)$$
$$\quad - (A_R k_A \beta V_{01} + A_H \beta V_{02})x_2 + (Q_{v1}\beta A_R + Q_{v2}k_A \beta A_H)x_1$$
$$\quad + (\beta A_R A_H - k_A \beta A_H A_R)x_1 x_2 + (-Q_{v1}\beta V_{02} + Q_{v2}k_A \beta V_{01})$$

Define the uncertain parameters set

$$\alpha = \begin{bmatrix} \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 & \alpha_5 & \alpha_6 & \alpha_7 & \alpha_8 \end{bmatrix}^T$$

as

$$\alpha_1 = V_{01}V_{02},$$
$$\alpha_2 = V_{02}A_H - V_{01}A_R,$$
$$\alpha_3 = \beta V_{02} + k_A \beta V_{01},$$
$$\alpha_4 = k_{leak}k_A \beta V_{01} + k_{leak}\beta V_{02},$$
$$\alpha_5 = A_R k_A \beta V_{01} + A_H \beta V_{02},$$
$$\alpha_6 = Q_{v1}\beta A_R + Q_{v2}k_A \beta A_H,$$
$$\alpha_7 = \beta A_R A_H - k_A \beta A_H A_R,$$
$$\alpha_8 = Q_{v2}k_A \beta V_{01} - Q_{v1}\beta V_{02}$$

Then,

$$g(x) = \alpha_1 + \alpha_2 x_1 - A_H A_R x_1^2 \geq 0$$

$$h_1(x) = \alpha_3 D$$

$$h_2(x) = -\alpha_4(x_3 - x_4) - \alpha_5 x_2$$
$$\quad + \alpha_6 x_1 + \alpha_7 x_1 x_2 + \alpha_8$$

Since $g(x) \geq 0$, define the Lyapunov function as

$$V = \frac{1}{2}g(x)z_{34}^2 \qquad (12)$$

The derivative of (12) is calculated as follows

$$
\begin{aligned}
\dot{V} &= \frac{1}{2}\dot{g}(x)z_{34}^2 + g(x)z_{34}\dot{z}_{34} \\
&= \frac{1}{2}\alpha_2 x_2 z_{34}^2 - A_H A_R x_1 x_2 z_{34}^2 + z_{34}\alpha_3 D\omega \\
&\quad + z_{34}\bigg( -\alpha_4(x_3 - x_4) - \alpha_5 x_2 \\
&\qquad + \alpha_6 x_1 + \alpha_7 x_1 x_2 + \alpha_8 \bigg) \\
&\quad - z_{34}\big(\alpha_1 + \alpha_2 x_1 - A_H A_R x_1^2\big)\dot{x}_{34d}
\end{aligned} \qquad (13)
$$

Here, the derivative of $\dot{x}_{34d}$ is calculated as

$$\dot{x}_{34d} = \ddot{x}_{1d} - k_1\ddot{z}_1 - k_2\dot{z}_2 = \ddot{x}_{1d} - k_1\ddot{z}_1 - k_2\big(\ddot{z}_1 + k_1\dot{z}_1\big)$$

Let $\hat{\alpha}_i$ is the estimated value of $\alpha_i, i = 1, 2, \ldots, 8$, we design the control input law as follows.

$$\omega = \frac{\omega_1 + \omega_2 + \omega_3}{(\hat{\alpha}_3 + \hat{\alpha}_4 x_1)D} \qquad (14)$$

$$\omega_1 = A_H A_R x_1 \big(x_2 z_{34} - x_1 \dot{x}_{34d}\big)$$

$$
\begin{aligned}
\omega_2 &= -\frac{1}{2}\hat{\alpha}_2 x_2 z_{34} \\
&\quad -\big(\hat{\alpha}_5 + \hat{\alpha}_6(x_3 - x_4) + \hat{\alpha}_7 x_2 + \\
&\quad +\hat{\alpha}_8 x_1 + \hat{\alpha}_9 x_1(x_3 - x_4) + \hat{\alpha}_{10} x_1 x_2\big) \\
&\quad +\big(\hat{\alpha}_1 + \hat{\alpha}_2 x_1\big)\dot{x}_{34d}
\end{aligned}
$$

$$\omega_3 = -k_3 z_{34} - k_4 D sign(z_{34})$$

where, $\omega_1$ is used to compensate the certain known factors, $\omega_2$ is the adaptive signal, which is employed to deal with uncertainties, and $\omega_3$ is the robust signal which deals the disturbance $d(t)$.

For simplicity, define

$$\alpha_g = \begin{bmatrix} \alpha_1 & \alpha_2 \end{bmatrix}^T$$

$$\alpha_{h1} = \begin{bmatrix} \alpha_3 & \alpha_4 \end{bmatrix}^T$$

$$\alpha_{h2} = \begin{bmatrix} \alpha_5 & \alpha_6 & \alpha_7 & \alpha_8 & \alpha_9 & \alpha_{10} \end{bmatrix}^T$$

The estimation of uncertain parameters $\hat{\alpha}_g$, $\hat{\alpha}_{h1}$ and $\hat{\alpha}_{h2}$ can be done as follows. Consider the Lyapunov function:

$$V_a = V + \frac{1}{2}\big(\alpha_g^T T_g^{-1}\alpha_g + \alpha_{h1}^T T_{h1}^{-1}\alpha_{h1} + \alpha_{h2}^T T_{h2}^{-1}\alpha_{h2}\big)$$

where, $T_g, T_{h1}, and\ T_{h2}$ are the positive definite constant diagonal matrixes. In order to ensure $\dot{V}_a \leq 0$, the update law is chosen as follows:

$$\dot{\hat{\alpha}}_g = \frac{1}{2}T_g z_{34}\big(\dot{\bar{g}}z_{34} - 2\bar{g}\dot{x}_{34d}\big)$$

$$\dot{\hat{\alpha}}_{h1} = proj_{\alpha_{h1}}\big(T_{h1}z_{34}\bar{h}_1\omega\big)$$

$$\dot{\hat{\alpha}}_{h2} = T_{h2}z_{34}\bar{h}_2 \qquad (15)$$

where,

$$\alpha_g^T \bar{g} = g(x)$$

$$\alpha_{h1}^T \bar{h}_1 = h_1(x)$$

$$\alpha_{h2}^T \bar{h}_2 = h_2(x)$$

and

$$proj_{\alpha_{h1}}(*) = \begin{cases} 0, & if\ \hat{\alpha}_{h1} = \alpha_{h1max}\ and\ * > 0 \\ 0, & if\ \hat{\alpha}_{h1} = \alpha_{h1min}\ and\ * < 0 \\ *, & otherwise \end{cases}$$

## 4. Experimental results

In this section, experiments for the system using the designed backstepping controller as described in section 3, are carried out. The controller is tested with two conditions: a unloaded motion and a bounded 16KN loaded motion. A sinusoidal signal is employed as reference position control.

$x_d$=100sin(0.1pt) [mm]

The control results are shown in fig. 4 and fig. 5. For unloaded condition, the effect of dead‐zone, while the pump changes direction, is shown clearly. When the pump changes its movement direction, there is always a peak error as seen at time 5.1s, 15.1s, and 25.1s on the error graph. As seen in fig.4, the developed backstepping control provides better response than the PID controller. The proposed backstepping control with adaptive laws also reduces the dead‐zone effect on the system response. However, the chattering phenomena still occurs in the system response.

In the 16KN loaded condition, while the PID

cannot maintain good response, the proposed controller still provides acceptable response. These experimental results prove that the designed controller have strong ability to be applied as the position control for a nonlinear system as the EHA.

## 5. Conclusions

A modified backstepping position control has been presented for a nonlinear EHA with uncertainties. The control structure is designed by selecting a special Lyapunov function, while all uncertain terms are adapted by selecting another Lyapunov function. The whole control structure is the combination of adaptive technique and a simple robust structure to compensate the nonlinearities and bounded disturbance. Experimental results prove that the proposed controller can obtain accurate performance even in the presence of an external disturbance.
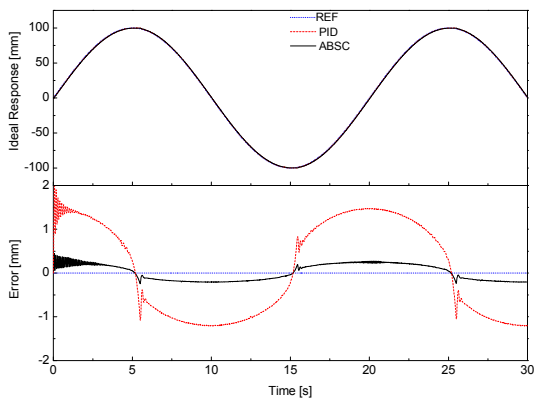


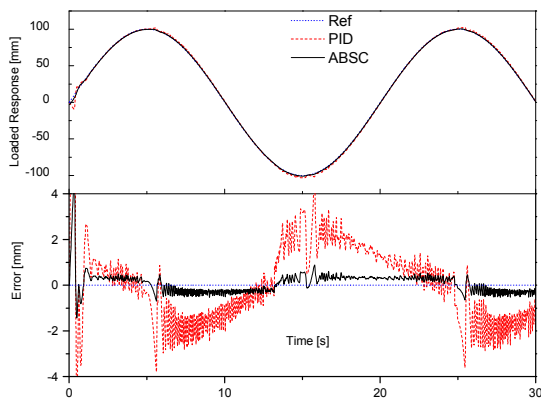Fig. 4 Sinusoidal response in no loaded condition



Fig. 5 Sinusoidal response in 16kN loaded condition

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