DC Motor Position Control for Pulley Axial Movement of an Electromechanical Dual Acting Pulley (EMDAP) CVT System

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Abstract: Currently hydraulic system has been used for changing transmission ratio of metal pushing V-belt Continuously Variable Transmission (CVT) with single acting pulley system. This paper introduces an alternative way of changing transmission ratio using an electromechanical actuator applied to dual acting pulley CVT system. This new system introduces two DC servomotors as actuators and power screw mechanisms as a means of shifting movable pulleys axially along transmission shafts. The primary motor is responsible for changing transmission ratio, while the secondary one is for preventing the metal belt from slipping. Since the methods of controlling these two motors are similar, this paper only discusses the primary part. Fuzzy PID control scheme is proposed for the DC servomotor position control. This controller drives the servomotor to regulate the axial movement of two movable pulley sheaves to shift the metal belt placed between the sheaves, and change the belt-pulley contact radius. Changing this contact radius means changing the transmission ratio. The fuzzy logic controller is used to improve the performance of the conventional PID considerably. Computer simulation results are presented to demonstrate the effectiveness of the proposed fuzzy PID controller as compared to that of the conventional fixed gain PID controller.

Keywords: *dual acting pulley CVT, position control, Fuzzy PID controller.*

1. INTRODUCTION

Continuously variable transmission (CVT) enables the engine to run at its fuel-efficient operating point for any vehicle load, due to its wide range coverage of transmission ratio, hence lowering the engine fuel consumption. Most current metal pushing V-belt CVTs are hydraulically actuated. Unfortunately, this type of CVT needs continuous force to keep CVT pulleys clamping the metal belt, and preventing the belt slip. This continuous energy consumption becomes the major loss in the hydraulic CVT system that could reduce CVT efficiency [1]. To overcome this energy loss, the electromechanical actuated CVT system becomes a viable solution, since this system only operates during changing the transmission ratio. The electromechanical actuated CVT with single acting pulley system was introduced in [2]. Slightly different with [2], this paper introduces a new electromechanical CVT with dual acting pulley system, utilizing two DC servomotors as actuators. This system adopts two movable pulley sheaves in both primary and secondary shafts to keep the belt position aligned in the center of shafts, even during the transmission ratio change, hence eliminating the belt misalignment effects. Long term application of this misalignment may damage the belt. The metal belt misalignment has been studied intensively in [3]. A pair of movable sheaves in each shaft is driven by two DC servomotors. The primary motor is used for changing the transmission ratio, while the secondary one is used for preventing the belt from slipping. Since the methods of controlling these two motors are similar, this paper only discusses the primary part.

PID (Proportional, Integral and Derivative) controller has been the basis in the simple linear control systems. The PID controller is a well-known and well–established technique for various industrial control applications. This is mainly due to its simple design, straightforward parameters' tuning, and robust performance. As actuators, DC servomotors are extensively used in many automatic controls, including drive for robotic manipulators, machine tools, rolling machines, photocopy machines etc. PID controllers are usually used to control these servomotors. Position controls utilizing PID can be seen in [4,5,6,7]. To design an effective PID controller, three gain parameters, namely, proportional gain, integral gain and derivative gain need to be specified properly. The conventional approach to determine the PID parameters is to study the mathematical model of the process and try to come up with a simple tuning law that provides a fixed set of gain parameters. One famous example of such approach is the Ziegler-Nichols method [8].

Fixed gain PID controller is suitable for fixed parameters processes that could be mathematically modeled using linear first or second order systems. However, an accurate model of a real industrial process is difficult to obtain, since the

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process itself may have complex characteristics such as nonlinearity, high order, delay-time, dead-time etc. that cannot be easily modeled using a simple linear system. In addition, the process may be affected by parameter variations due to temperature, ageing components, noise, and load disturbance. For these complex processes, tuning laws based on these inaccurate models are no longer adequate to attain the controller gains properly.

In order to increase the capabilities of the PID controllers in improving their performance for wide range of industrial process applications, new features that retain their basic characteristics should be included, so that industrial practitioners can still take advantages of their knowledge and experiences. For this reason, the use of fuzzy logic controller (FLC) seems to be appropriate, since the FLC presents an algorithm for translating an expert knowledge-based linguistic control strategy into an automatic control strategy [9]. Fuzzy-logic-based PID controllers offer knowledge representation and learning capabilities to tackle a wide range of complex dynamical systems, which may be ill defined or subjected to numerously varying parameters. Auto tuning of PID controller using Takagi-Sugeno type fuzzy logic controller is proposed for performing the pulley axial position control of the EMDAP CVT system.

2. ELECTROMECHANICAL DUAL ACTING PULLEY CVT

The electromechanical dual acting pulley CVT (EMDAP CVT) system utilizes two DC servomotors ac actuators. The system consists of two sets of pulleys, namely primary pulley placed on input fixed shaft, and secondary pulley placed on secondary fixed shaft. Each set of pulley has two movable sheaves that can be shifted axially along the shaft. Output shaft of the DC servomotor is directly connected to a series of gear reducers and power screw mechanism to initiate the axial pulley sheaves' movement. Based on this arrangement, the DC servomotor enables to control the sheaves' movements directly. A Van Doorne's metal pushing V-belt is placed between pulley sheaves, and runs on the surface of the sheaves. This metal belt connects the primary and secondary to transmit the power and torque from the input to the output shaft by means of friction between the belt and the pulley contact [10,11]. The contact radius of the belt with primary pulley (R_p) and the contact radius of the belt with secondary pulley (R_s) determines the transmission ratio. The closer the distance between the movable sheaves, the bigger the contact radius will be. The primary and secondary parts of the CVT system have the same components. The components of each part (primary or secondary) consist of a dc servo motor, a gear reducer with ratio of (30:1), a gear reducer with gear ratio of (60:14), power screw mechanism, and two movable metal pulley sheaves for clamping the metal pushing belt. The block diagram of the EMDAP-CVT system can be seen in figure 1. In laboratory experiments, parameters that can be directly measured are X_p (axial position of primary pulley), X_s (axial position of secondary pulley), ω_p (angular speed of primary pulley), ω_s (angular speed of secondary pulley), T_p (torque of primary pulley) and T_s (torque of secondary pulley).

The primary motor actuates the primary pulley movement for transmission ratio change, while the secondary motor actuates the secondary pulley movement for clamping force. A spring disc is inserted in the back of each secondary pulley sheave to provide continuous clamping force to the belt, and to reduce excessive slip during transmission ratio change. When the CVT is on an underdrive position, the primary belt radius is minimum while the secondary belt radius is maximum. When the ratio change is called, the primary motor will actuate the primary pulley axially to the new value of primary radius, and at the same time the secondary motor will actuate the secondary pulley axially to provide the optimal clamping force for preventing belt slip. These movements will stop if the desired ratio is achieved. When the CVT is on the overdrive position, the primary belt radius is maximum, while the secondary belt radius is minimum.

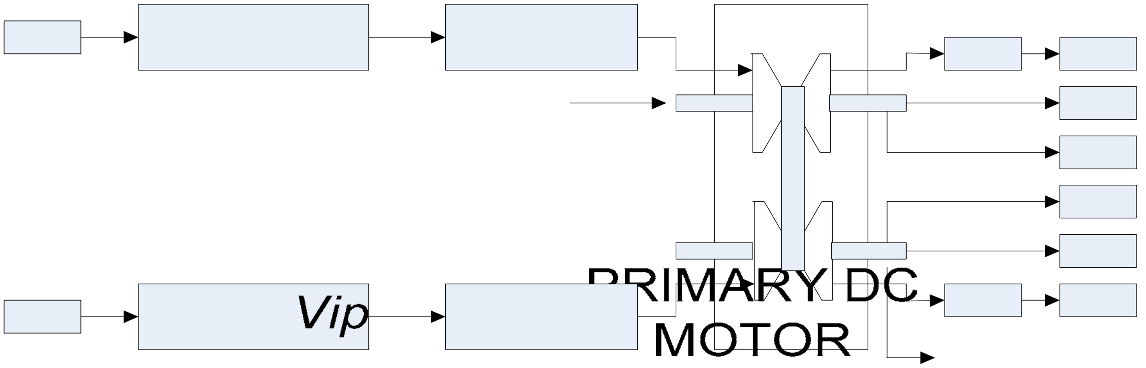

Figure 1. The block diagram of the EMDAP-CVT

3. SYSTEM MODELING

3.1. Modeling of DC Servomotor

The dynamic model of the DC servomotor is represented as follow:

$$V_a = L_a \frac{di_a}{dt} + R_a . i_a + K_a \omega_a \quad (1)$$

$$T_m = K_m . i_a \quad (2)$$

$$T_m - T_L = J_m (d\omega/dt) + B_m (d\theta/dt) \quad (3)$$

By using LaPlace Operator $s = d/dt$, then

$$V_a = sL_a i_a + R_a i_a + K_a \omega \quad (4)$$

$$V_a - K_a . \omega = s.L_a . i_a + R_a . i_a \quad (5)$$

$$T_m - T_L = J_m . s . \omega + B_m . s^2 . \omega \quad (6)$$

$$\theta = \omega / s \quad (7)$$

Where :

V_a : Motor Voltage [V]
L_a : Motor Inductance [H]
i_a : Motor Current [A]
R_a : Motor Resistance [Ω]
K_a : Back emf constant [mV/(rad/sec)]
ω : Motor shaft angular velocity [rad/sec]
θ : angular displacement [rad]
T_m : Motor Torque [Nm]
K_m : Torque Contant [Nm/A]
T_L : Load Torque [Nm]
Jm : Motor Inertia [Nm.sec^2]
Bm : Viscous friction coefficient [Nm/rad/sec]

3.2. Gear Reducer and Power screw Mechanism

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A gear reducer serves as a speed reducer and torque multiplier. The gear reducers are coupled with the servomotor shaft. The gear reducer output is connected to power screw mechanism for shifting the pulley sheaves. There are two gear reducers employed in the EMDAP-CVT system. The first one has ratio of (30:1), while the second one has the ratio of (60:14). The total gear ratio of these reducers is (128.57:1). The power screw mechanism is used to move the pulley sheaves axially. It converts every 360° of rotation into 2 millimeters axial movement. The combination of gear reducers and power screw mechanism is used to help the motor in providing significant torque to turn the power screw mechanism.

Torque required by power screw to lift the load (increasing pulley clamping force) is given by:

$$T_{Lu} = F_c \tfrac{dm}{2} \frac{\pi.f.dm + l}{\pi.dm - f.l} \tag{8}$$

Torque required by power screw to release the load (reducing pulley clamping force) is given by:

$$T_{Ld} = F_c \tfrac{dm}{2} \frac{\pi.f.dm + l}{\pi.dm + f.l} \tag{9}$$

where :

T_{Lu} : Torque for lifting load [Nm]
T_{Ld} : Torque for lowering load [Nm]
dm : mean diameter of power screw = 0.08551 [m]
F_c : Axial compressive force (clamping force) [N]
f : friction of power screw surface contact = 0.16
l : pitch of power screw = 0.002 [m]

4. Proposed Controller

This paper proposes a Fuzzy-PID controller to control the DC servomotor system such that the axial-pulley position satisfies the desired set point. The common problem of tuning PID is dealing with specifying three gain parameters to meet a certain requirement of control specifications, such as set-point following, load disturbance attenuation, robustness due to model uncertainties, and noise rejection [12]. Many different techniques have been proposed in the literature to cope with these tuning problems. The use of Ziegler-Nichols formula for tuning the PID parameters usually gives a good result in load disturbance attenuation, but poor in both lowering the overshoot and reducing the settling time. These two aspects are mainly triggered by the selection of high proportional gain. To cope with this problem, a fuzzy logic controller is proposed to obtain the suitable weight value to adjust the proportional gain with respect to the current value of the system error (*e*) and its change of error rate (*de*). The block diagram of the proposed controller scheme is given in the fig. 2.

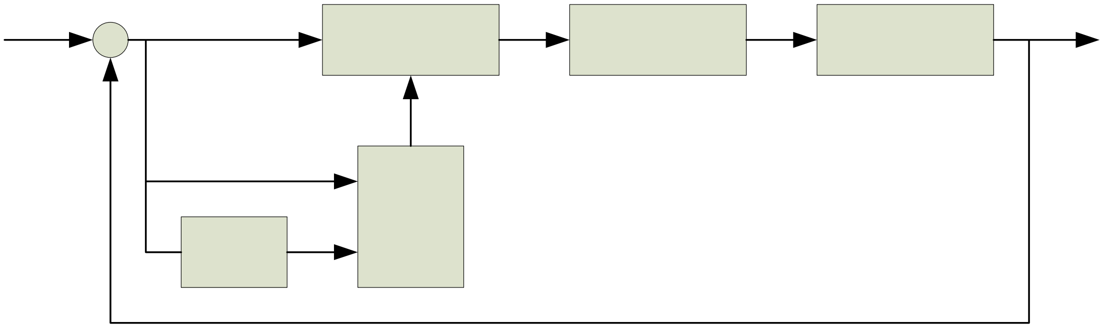


Figure 2. Block diagram of the Fuzzy-PID controller

4.1. Parameter Tuning for PID Controller

The transfer function of a PID controller has the following form:

$$G_{PID} = K_p + K_i / s + K_d s \qquad (10)$$

where K_p, K_i, *and* K_d are the proportional, integral, and derivative gains, respectively. Another useful equivalent form of the PID controller is given by:

$$G_{PID} = K_p (1 + 1/(T_i s) + T_d s \qquad (11\,)$$

where $T_i = K_p/K_i$ and $T_d = K_d/K_p$. T_i and T_d are the integral time constant and the derivative time constant, respectively.
The tuning objective is to determine the suitable value of three parameters (K_p, K_i, *and* K_d) to satisfy certain control specifications. In order to obtain the initial parameters of PID controller, the Astrom-Hagglund method [13] will be used to determine the values of critical period of waveform oscillation (T_c) and critical gain (K_c). These two values could be obtained by running the closed loop control of DC servomotor system utilizing relay feedback as a controller. The oscillation period of the output waveform is considered as the critical period attained from a proportional feedback. Based on this critical period (see fig. 3), the critical gain can be derived as follow:

$$K_c = \frac{4d}{\pi a} \qquad (\,12)$$

Where *d* is the amplitude of the relay output, and *a* is the amplitude of the waveform oscillation.
Based on these two values, the PID parameters (K_p, T_i , and T_d) can be specified using Ziegler-Nichols formula [8] (see Table 1.).

Table 1. Ziegler-Nichols parameter tuning.

	K_p	T_i	T_d
P	0.5 K_c		
PI	0.45 K_c	0.85 T_c	
PID	0.6 K_c	0.5 T_c	0.125 T_c

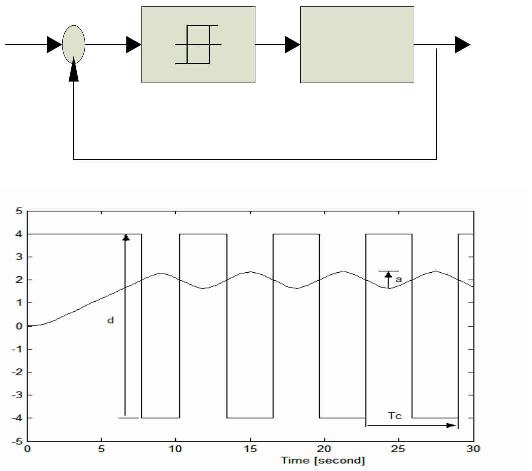
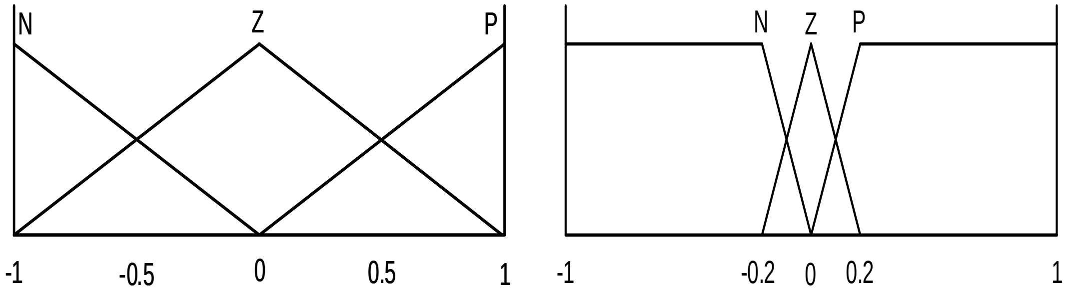


Figure. 3 The relay feedback controller

4.2. Fuzzy Auto Tuning

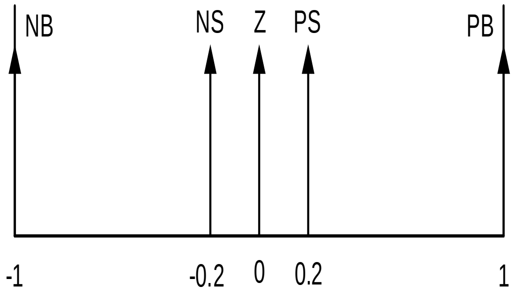
Fuzzy logic is used to perform online tuning for PID parameters. By using Astrom and Hagglund method, the values of critical period of waveform oscillation (T_c) were found, then by applying equation (4), the critical gain (K_c) was obtained. Based on these two values, by using equation (9), (10), and equations in table 1, the initial parameters of the PID controller could be found. A tuning algorithm proposed in this paper only tunes the proportional gain (K_p) of the PID controller.

The fuzzy auto-tuner takes two inputs: the error (*e*) and the change error rate (*d*e) of the output response. To normalize these inputs into the range of [-1,1] , these inputs are scaled by two coefficients, K_e and K_{de} respectively. The fuzzy system can be started to operate at a certain error value by specifying the value of K_e. This paper selects $K_e=10$, meaning that the system will effectively operate when the output error is in the range of [-0.1,0.1]. The K_{de} can be set initially to '1'. Three triangular membership functions (see fig.4) are defined for each input (N=Negative, Z=Zero,P=Positive), while five constant values of Takagi-Sugeno type in the range of [-1,1] is defined for the output (NB=Negative Big, NS=Negative Small, Z=Zero,PS=Positive Small,PB=Positive Big).



(a) error

(b) the change of the error



(c) Output

Figure 4. Membership function of input and output

The error ($e(k)$) and the error change rate ($de(k)$) are defined as follow:

$$e(k) = x_r(k) - x_a(k) \quad (13)$$

$$de(k) = e(k) - e(k-1) \quad (14)$$

The fuzzy output (Y_f) is the singleton value in the range of [-1, 1] of the Takagi-Sugeno Type. This output value is then multiplied by the proportional gain (K_p) and then summed with other PID gains to give the overall controller gain (G_c) :

$$G_c = Y_f * K_p + K_i + K_d \quad (15)$$

The fuzzy rules to determine the output fuzzy (Y_f) is the following equation:

$$R^i: \text{if } e(k) \text{ is } A_j \text{ and } de(k) \text{ is } B_j \text{ then } Y_{fji} \quad (16)$$

Where i $(i=1,\ldots,9)$ is the number of rules.

The rule justification is based on the “scale mapping” method developed by King and Mamdani [9]. This justification is done by referring to a closed system trajectory in a phase plane. The control rules of the consequence of (Y_f) are determined from the error curve of the system step response [8] (see fig. 5.). This justification requires both knowledge of controller parameter adjustment based on the phase plane analysis, such as overshoot and rise time, and intuitive feeling of the behavior of the closed loop system. The prototype of the fuzzy control rules is given in table 2. While the justification of a fuzzy control rules is presented in table 3.

Defuzzifcation is needed for the fuzzy logic controller to convert its internal fuzzy output variables into crisp values usable for the controlled system. This paper will adopt the weighted average method as following:

$$y_f = \frac{\sum_{i=1}^{n} w_i c_{j,i}}{\sum_{i=1}^{n} w_i} \qquad (17)$$

Where :

n is the number rules, $C_{j,I}$ is the vale of the center of gravity of the fitness of *i-th* rule in the premise, and the fitness (w_i) is defined as:

$$w_i = \mu_{Aj}(e(k)) x \mu_{Bj}(de(k)) \qquad (18)$$

j=1,2,3, i=1,2,3

This type of defuzzification method is selected due to its simple and fast computation [7].

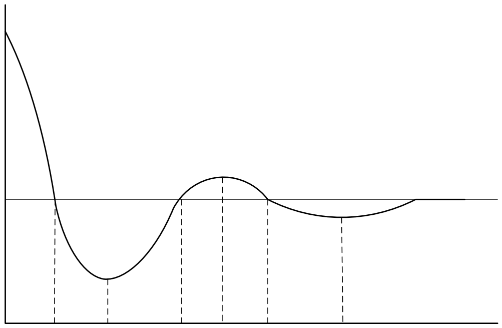


Figure 5. Error curve of output

Table 2. The prototype of the fuzzy control rules

Rule No.	e	de	Y_f	Reference Point
1	P	Z	PB	a,e
2	Z	N	NS	b
3	N	Z	NB	c
4	Z	P	PS	d
5	Z	Z	Z	f

Table 3. the justification of a fuzzy control rules

Rule No.	e	de	Y_f	Reference range
6	P	N	PB	1,5
7	N	N	NB	2
8	N	P	NB	3,6
9	P	P	PB	4

a

1

5. SIMULATION STUDIES

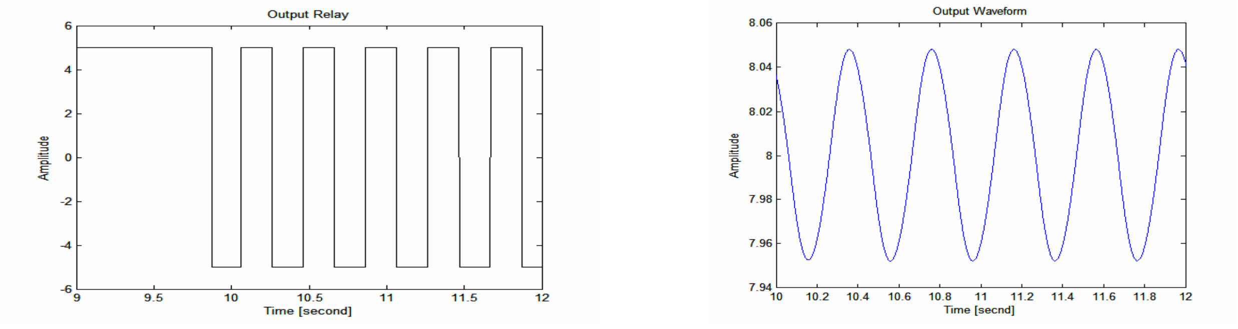
Simulation studies of the proposed Fuzzy-PID controller are carried out in order to investigate its effectiveness in this position control application. In these studies, the DC servomotor has the following important parameters as shown in Table 4.

Table 4. DC servomotor parameters

Parameters	**Values**
Motor Voltage	24 V
Armature Resistance	0.03 Ω
Armature Inductance	0.1 mH
Back emf Constant	7 mV/rpm
Torque Constant	0.0674 N/A
Nominal Torque	1.6 Nm
Nominal Speed	3000 rpm
Rotor Inertia	0.1555e-4 $N.sec^2$

Based on these parameters, the simulation of the system was investigated. The simulation of the controller was performed using MATLAB/FUZZY-SIMULINK packages. Control performance is determined based on percent overshoot (POS), and settling time t_s, and steady state error e_{ss}. Two types of input excitation: step, and sinusoidal waveform, are used to examine the performance of the conventional PID and the Fuzzy-PID controllers. The initial proportional gain will be set to the same value to ensure reasonable comparisons between these two controllers.

In order to obtain initial parameters of PID, the Astrom-Hagglund method based on a relay feedback controller is carried out to attain the critical period of waveform oscillation (T_c) and critical gain (K_c). The relay feedback controller is used in a closed loop control application. The amplitude of the relay controller is set to 10 since the input voltage in the range of [-5,+5 volts] is needed to drive the servo system. From simulation results, these following parameters are found: $T_c = 0.4$ s, $a = 0.1$, and $d = 10$ (see fig.6).



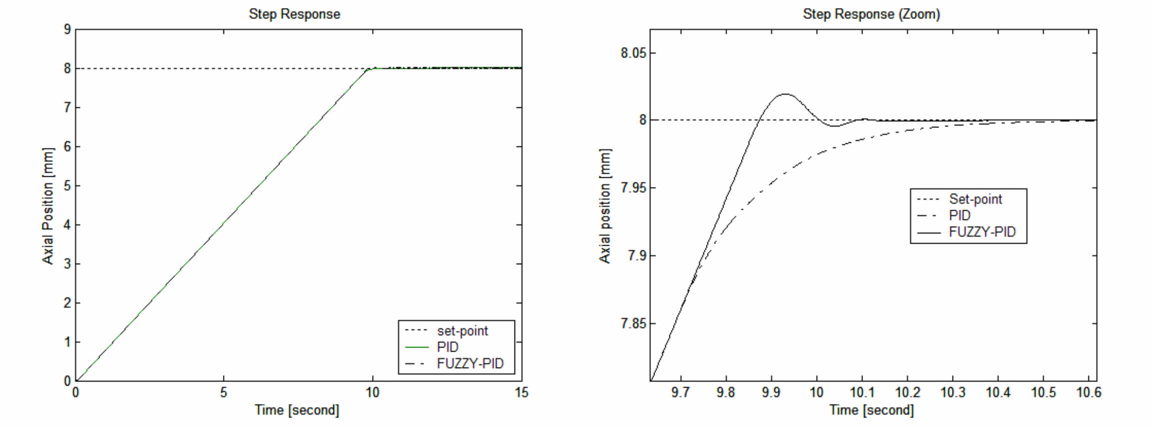
(a) Relay output

(b) Waveform of oscillation

Figure 6. The results of relay feedback controller

By using equation (12), the critical gain (K_c) is 127.4. Then, the Ziegler-Nichols formula (see table 2.) is applied to find the values of K_p, T_i, and T_d. Finally, by using these values and equations (10,11), the three parameters of PID can be specified as follows: $K_p=76.4$, $K_i=636.9$, and $K_d=3.8$. From these data, it can be seen that the value of the integral gain (K_i) is much bigger compare to other gains. By closely looking at the small amplitude of waveform oscillations, it can be seen that the servo system exhibits a small steady state error of about 1.25 % (for set-point = 8 mm). This condition can be understood, since the servo system utilizes gear reducers with a total ratio of about (128.57:1) to supply pulley clamping force, hence slowing down the axial pulley movement significantly. Based on this fact, it is reasonable to say that the integral gain was not used for controlling this kind of servo system, since the system behavior has alredy had a small tolerable steady state error.

Figure 7. shows the output response of the conventional PID and the Fuzzy-PID when the step input of 8 mm is applied. From figure x., the percent overshoot of the Fuzzy-PID controller is little bit bigger (about 0.25 %) than the PID. The percent overshoot of about 0.25% is close to zero and still acceptable, In case of settling time, the Fuzzy-PID is faster than the PID one.

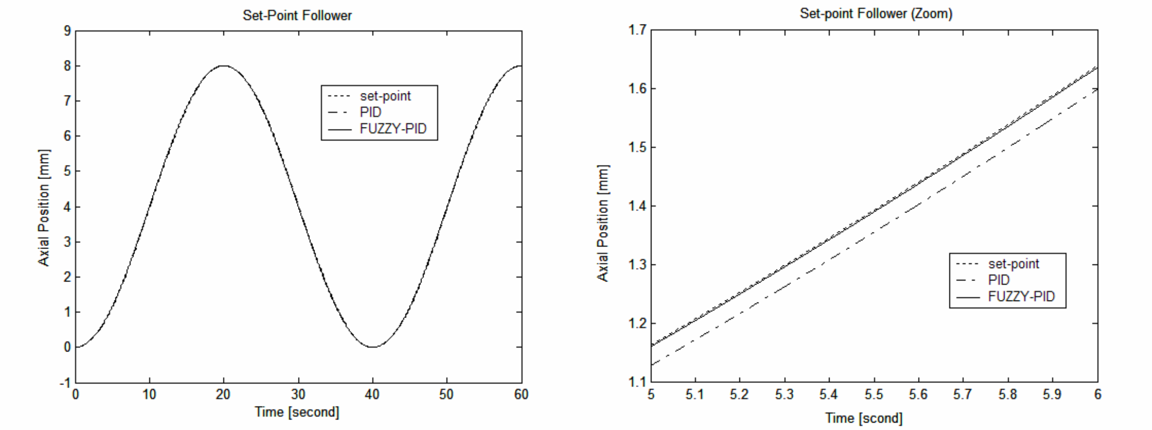


(a). output response

(b) Zoomed output response

Figure 7. Output response when step input is applied

Figure 8. and figure 9 show the output responses of the sinusoidal wave excitation. From these figures it can be seen that the Fuzzy-PID has smaller position error compared to the PID one. Thus, the Fuzzy PID gives good tracking trajectory with good response and minimum (tolerable) error as shown in these figures.



(a) set-point follower

(b) Zoomed set-point follower

Figure 8. Set-point follower

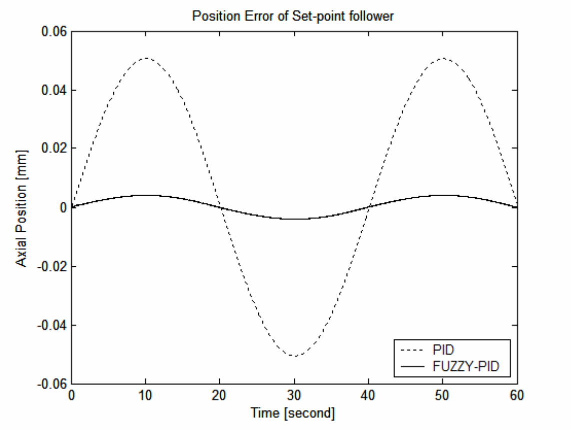


Figure 9. Position error of set-point follower

Overall, the Fuzzy-PID controller performs better than the conventional PID especially in terms of settling time and tracking. In terms of percent overshoot and steady state error, both controllers have good performance.

6. CONCLUSION

The conventional PID is initially tuned using Astrom-Hagglund method and Ziegler-Nichols formula. Both proportional and derivative gains of the PID are used to control the servomotor system. The integral gain is not used, since this servomotor system itself exhibits a small tolerable steady state error. The proposed controller utilizes a fuzzy logic controller to tune the proportional gain of the PID controller to improve the PID performance. The simulation results have shown that the proposed Fuzzy-PID controller can perform better in terms of settling time and trajectory tracking. In terms of percent overshoot and steady state error, both controllers perform well. This simulation studies have demonstrated that the Fuzzy Logic Controller can be proposed to improve the performance of the conventional PID controller especially in terms of settling time and trajectory tracking.

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