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A Study on Hydraulic Load Simulator Using Self Tuning Grey Predictor – Fuzzy PID

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Abstract: Nowadays, considering the development of the industry, hydraulic actuator has a wide range of application fields. This paper presents a kind of hydraulic load simulator for conducting performance and stability test for control force of hydraulic hybrid systems. A grey prediction model GM(1,1) combined with a fuzzy PID controller is suggested to apply for this system. Furthermore, fuzzy controllers and a tuning algorithm are used to change the Grey step size to improve the control quality. The grey prediction compensator can improve the system settle time and overshoot problems. Simulations and experiments are carried out to evaluate the effectiveness of the proposed control method applied for hydraulic systems with varied external disturbance as in real working conditions.

1. INTRODUCTION

Hydraulic systems have been widely used in modern industries because of their advantages. Hybrid actuator is known as the PowerShift which shifts from high-speed electric to high-force hydraulic, thus creating a sleeker, cleaner, more energy efficient way to produce high forces. Contrary to the simplicity of hybrid actuators, the control problem is very complicated because of their nonlinearity and large uncertainties due to unstableness of some hydraulic parameters such as bulk modulus, compressibility of oil or viscosity of oil (Yao *et al.*, 2000). As a result, many hybrid actuator models were fabricated for doing researches on controlling force or pressure with best performances (Su *et al.*, 2001; Li, 2002).

In control process, to eliminate or reduce the unknown disturbance at a large scale, several force control strategies have been proposed (Chen *et al.*, 1990; Conrad *et al.*,1987). Conventional PID controllers are commonly used in industry due to their simplicity. Meanwhile, fuzzy control imitating the logical thinking of human and being independent on accurate mathematical model of the controlled object can overcome some shortcomings of traditional PID (Lee *et al.*, 2004; Ahmed *et al.*). However, the design of fuzzy rules depends largely on the experience of experts or input-output data. There is no systematic method to design and examine the rules number, input space partition and membership function (Truong et al., 2007). Hence, another controller such as prediction analysis is necessary to be combined with the fuzzy PID to overcome this weakness.

The objective of this paper is to introduce a new model of hydraulic load simulator which contains a new hybrid actuator and a disturbance generator to develop force control strategy using a self tuning grey predictor based fuzzy PID controller. The first piece of research on grey systems, entitled "The Control Problems of Grey Systems," (Deng, 1982) in which the grey theory is distinguished with its ability to deal with the systems that have partially unknown parameters. The grey prediction technique has been successfully employed to solve many engineering problems including robot position control, fluid engineering control and manufacturing systems (Kayacan *et al.*, 2006; Lee *et al.*, 2006).

A fuzzy PID controller with a grey predictor whose step size is changed by fuzzy controllers and a self tuning algorithm is presented in this paper. Then it makes a simple close-loop control for the new hybrid actuator. In order to verify the overall control system, a co-simulation between AMESim (Imagine, 2004) and Simulink - Matlab is chosen. Simulation results show the effectiveness of using the proposed control method for the hybrid actuator to reach the control target of the new hybrid actuator.

2. LOAD SIMULATOR SYSTEM

The schematic diagram of the new hydraulic load simulator is shown in Fig. 1. The system hardware consists of a new hybrid actuator, a computer included PCI-bus multifunction cards and another one hydraulic circuit generating disturbances.

In this model, the new hybrid actuator is a combination of AC servo motor (SGMGH-30PCA21), piston pump, reservoir and hydraulic control circuit. The operation at the number of revolutions which meets the machine requirements (flow rate and pressure) reduces power losses, provides energy savings. The pressure oil line from the pump without a control valve minimizes pressure losses and substantially reduces the heat generation of hydraulic fluid. About the operation of the hybrid actuator, the bidirectional rotational pump is used and

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driven by the AC servo motor so that the pump can supply pressured oil in both directions. The pump is well equipped as a hydraulic driving force. With the servo drive, the digital control parameter setting facilitates to operate the system and its maintenance.

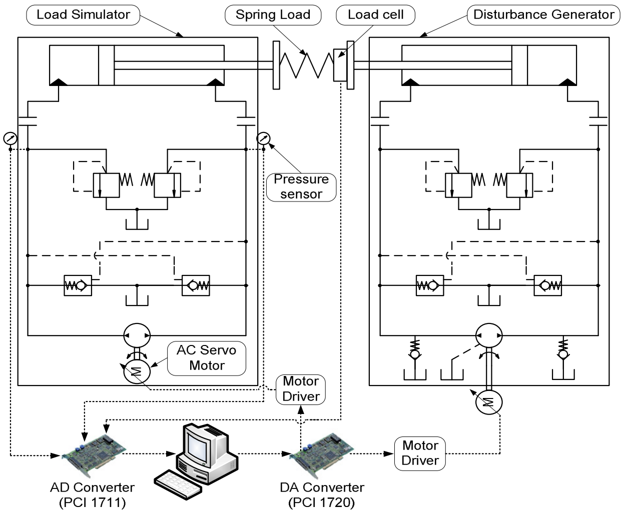


Fig. 1. Schematic diagram of hydraulic load simulator

In addition, to prove the effectiveness of the presented control method when the system operates in the real conditions, another hydraulic circuit is applied for generating disturbance. The disturbance is verified by the compatible computer with PCI cards. A compression spring with 519 kN/m stiffness is connected between the hybrid actuator and the disturbance generator. A load cell YG38-T5 is used to get the feedback force signal. The control deviation of the reference signal and sensor signal is measured on the PC and the control signal is sent from the PC to the servo drive to drive the AC servo motor by using PCI cards, consequently forming a feedback control loop.

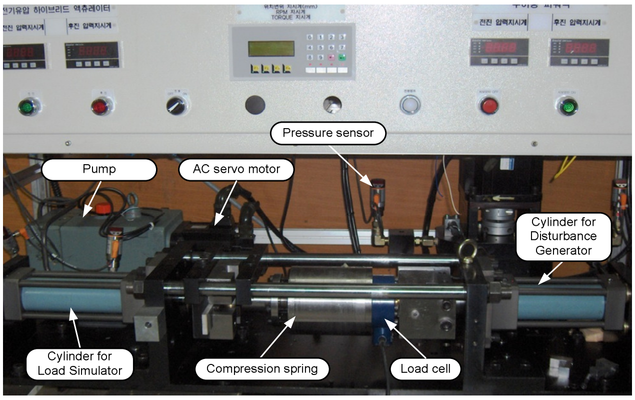


Fig. 2. Photograph of experimental apparatus

A PC (AMD Athlon 1.9 GHz) included two PCI-bus data acquisition & control cards (Advantech cards, PCI 1711 and PCI 1720) is used to receive, process feedback signals and then make the output signals to control the motors. The control algorithm is built within Simulink environment combined with Real-time Windows Target Toolbox of Matlab. Fig. 2 displays the experimental apparatus.

3. FORCE CONTROLLER DESIGN

3.1 Analysis of Force Control

Force control in hydraulic actuators is a difficult problem because of their nonlinearity and large uncertainties. PID controller is the most widely used in modern industry due to its simple control structure and easy design. But the conventional PID controllers do not yield reasonable performance over a wide range of operating conditions because of the fixed gains used. Then the PID parameters need to be adjusted by a fuzzy set automatically. However, the design of fuzzy rules depends on largely the experience of experts or input-output data. Meanwhile, grey prediction technique has the ability to deal with the systems that have partially unknown parameters. The prediction technique has been successfully employed to solve many engineering problems including robot position control, fluid engineering control and manufacturing systems. So, this paper presents a self tuning grey predictor based fuzzy PID controller to apply for load simulator system. A self tuning fuzzy PID controller with a grey predictor is powerful for the system to improve the control performance as fast response, minimal overshoot and stability. Furthermore, fuzzy controllers and a tuning algorithm are used to change the Grey step size to improve the control quality, adopt and stabilize systems rapidly and effectively. The overall structure of the proposed controller is shown in Fig. 3.

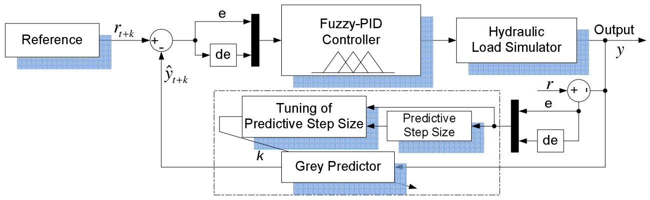


Fig. 3. Structure of proposed control algorithm

To control force for hybrid system, a conventional PID controller is combined with fuzzy laws. The control signal can be expressed in the time domain as:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt} \qquad (1)$$

where $e(t)$ is the error between desired force set point and the output, $de(t)$ is the derivation of error, $u(t)$ is the control signal used to control velocities of AC servo motor, K_p is proportional gain, K_i is integral gain and K_d is derivative gain.

3.2 Self Tuning Fuzzy PID Controller

Form (1), three coefficients K_p, K_i and K_d are tuned by using the fuzzy tuner. The rules designed are based on the characteristic of hydraulic load simulator such as slow response, non-linearity, large uncertainties existing in hydraulic systems and properties of the PID controller. The detailed fuzzy-PID scheme applied to hydraulic load simulator is shown in Fig. 4. There are two inputs to the controller: error $e(t)$ and derivative of error $de(t)$. The ranges of these inputs are from 0 to 1, which are obtained from the absolute values of the system error and its derivative through the gains. Three outputs of the fuzzy set are *kp*, *ki* and *kd*. The ranges of the outputs are from 0 to 1.

For each input or output variable, four membership functions are used. Here, "Z", "S", "M" and "B" are "Zero", "Small", "Medium" and "Big", respectively. Details of the fuzzy member ship functions are shown in Fig. 5. Then these output values are substituted into the following equations to compute the coefficients K_p, K_i and K_d in (2)

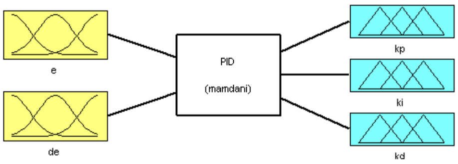


Fig. 4. Fuzzy inference block

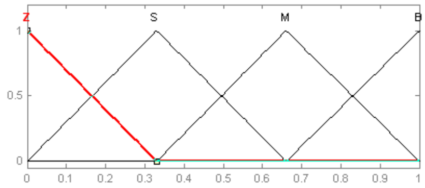


Fig. 5. Membership functions for e(t), de(t), kp, ki and kd

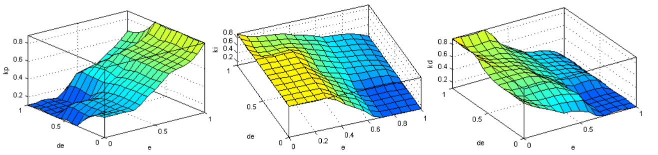
$$\begin{cases} kp = \dfrac{K_p - K_{p\min}}{K_{p\max} - K_{p\min}} \\ ki = \dfrac{K_i - K_{i\min}}{K_{i\max} - K_{i\min}} \\ kd = \dfrac{K_d - K_{d\min}}{K_{d\max} - K_{d\min}} \end{cases} \tag{2}$$

where, [K_{pmin}, K_{pmax}], [K_{imin}, K_{imax}] and [K_{dmin}, K_{dmax}] are the ranges of K_p, K_i and K_d, respectively. Table 1 shows the rule tables for the fuzzy PID controllers.

Table 1. Rule table of fuzzy PID controller

(k_p, k_i, k_d)		$\lvert e(t)\rvert$			
		Z	S	M	B
$\lvert de(t)\rvert$	Z	(S,B,M)	(S,B,S)	(M,VS,VS)	(B,VS,VS)
	S	(VS,B,M)	(S,B,M)	(M,VS,VS)	(B,VS,VS)
	M	(VS,B,B)	(VS,B,M)	(M,S,S)	(B,VS,VS)
	B	(VS,B,B)	(VS,M,B)	(S,S,S)	(M,VS,VS)

In this paper, the "centroid" method is used for defuzzication to gain the accurate values which are then sent to PID controller to control the AC servo motor of the hybrid actuator. The rule sets are established in surfaces in Fig. 6.



(a) *kp* tuner (b) *ki* tuner (c) *kd* tuner

Fig. 6. 3D rule view of fuzzy tuners

3.3 Grey Prediction

Grey predictor can predict the future outputs of system with high accuracy without knowing the mathematical model of the real system. In grey prediction theory, GM(n,m) denotes a grey model, where n, m are respectively the order of the difference equation and the number of variables. The model skill of grey prediction is to conduct accumulated generating operating on original sequences. The resultant new series is used to establish difference equation to calculate coefficients via least-square method. The accumulated generating series prediction model value is then obtained. The value can be returned to estimate the time-domain by means of inverse accumulated generating operation. GM(1,1) - the most popular grey model used for prediction purpose is as "Grey Model First Order One Variable".

Grey predictor – GM(1,1)

The prediction procedure is as followed:

Step 1: At least four output data are needed to approximate a system. For a non-negative time series, collect *n* raw data:

$$y^{(0)} = \left\{ y^{(0)}(1), y^{(0)}(2), \ldots y^{(0)}(n) \right\} \tag{3}$$

Step 2: Take the accumulated generating operation (AGO) to obtain $y^{(1)}$ from $y^{(0)}$:

$$y^{(1)}(k) = \sum_{i=1}^{k} y^{(0)}(i), k = 1, 2, \ldots, n \tag{4}$$

Step 3: Apply a consecutive neighbor generation $z^{(1)}$ from $y^{(1)}$ by the following mean generating operation (MGO):

$$z^{(1)}(k) = 0.5y^{(1)}(k) + 0.5y^{(1)}(k-1); k = 2, 3, \ldots, n \tag{5}$$

Step 4: Establish grey differential equation of GM(1,1):

$$y^{(0)}(k) + az^{(1)}(k) = b \tag{6}$$

In which, parameter [*a*, *b*] can be obtained by using the least-square method as followings:

$$\hat{a} = \begin{bmatrix} a \\ b \end{bmatrix} = \left(B^T B\right)^{-1} B^T Y \tag{7}$$

$$B = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z^{(1)}(n) & 1 \end{bmatrix}, Y = \begin{bmatrix} y^{(0)}(2) \\ y^{(0)}(3) \\ \vdots \\ y^{(0)}(n) \end{bmatrix} \tag{8}$$

Step 5: Set up the prediction model GM(1,1) as:

$$\hat{y}^{(1)}(k+1) = \left(y^{(1)}(1) - \frac{b}{a} \right) e^{-ak} + \frac{b}{a} \tag{9}$$

$$\hat{y}^{(0)}(k+1)=\hat{y}^{(1)}(k+1)-\hat{y}^{(1)}(k) \qquad (10)$$

Step 6: Calculate the predictive output at time sequence $(n+p)^{th}$ step:

$$\hat{y}^{(1)}(n+p)=\left(y^{(1)}(1)-\frac{b}{a}\right)e^{-a(n+p-1)}+\frac{b}{a} \qquad (11)$$

$$\hat{y}^{(0)}(n+p)=\hat{y}^{(1)}(n+p)-\hat{y}^{(1)}(n+p-1) \qquad (12)$$

where p is the step size of the grey prediction.

Fuzzy predictor step

First, a fixed step size grey predictor is considered. Using a small step will speed up the system response but cause large overshoot or oscillation. Otherwise, a large one will reduce the overshoot but increase the rise time. Hence, the step should be self-adjusting. In this paper, a fuzzy controller to generate the step size is proposed. The configuration of the fuzzy step size is shown as in Fig. 7. There are two fuzzy inputs: error $e(t)$ and derivation of error $de(t)$ and one output is the step size p_{fuzzy} of the grey predictor. The membership functions of these fuzzy sets are shown in Fig. 8. The "centroid" method is used for defuzzication to gain the accurate value p_{fuzzy}. As a result, the rule sets are established and shown in surfaces in Fig. 9.

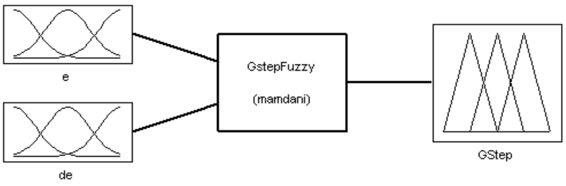
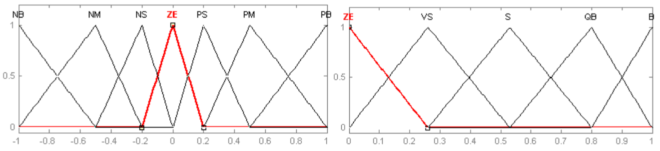


Fig. 7. Structure of the fuzzy inference block



(a) Inputs (b) output

Fig. 8. Membership functions of fuzzy predictor step

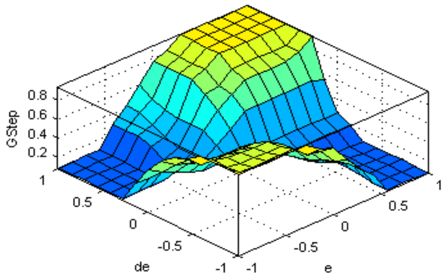
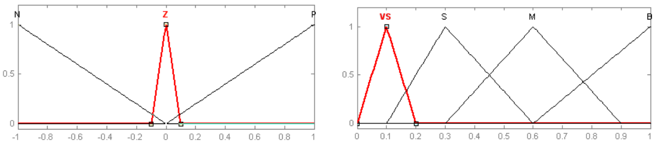


Fig. 9. Fuzzy step size controller – 3D rule view

Self tuning predictor step

A parameter γ considered as an evaluation coefficient is used. This factor is substituted in the learning algorithm to get the current predictor step size based on the last step (p_{t-1}) and the given step p_{fuzzy} by the fuzzy predictor step part. Therefore, it is capable to evaluate the status of the current state if it is appropriate for the control target or not. In order to obtain the above coefficient, a fuzzy set of two inputs and one output is constructed. The membership functions of the inputs (error $e(t)$ and derivation of error $de(t)$) and output (assess factor γ) are as shown in Fig. 10. The fuzzy idea is described in Fig. 11.



(a) Inputs (b) Output

Fig. 10 Membership functions

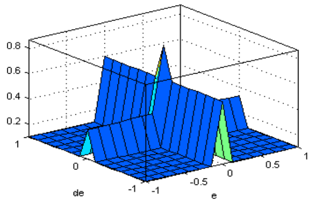


Fig. 11 Fuzzy evaluation factor – 3D rule view

The factor γ obtained from the fuzzy inference is then applied in the following equation:

$$p(t)=\gamma p(t-1)+(1-\gamma)p_{fuzzy} \qquad (13)$$

The step size p_t are sent to the grey predictor to calculate the predictive output at time sequence $(n+p)^{th}$ step by (12).

4. SIMULATION AND EXPERIMENTAL RESULTS

4.1 Load simulator model

The simulation software AmeSim is used to model the hydraulic system. Fig. 12 shows the AMESim model of the load simulator. AmeSim generates C-files for the actuator model and creates a DLL for the model. The DLL is then used in the simulation model in Simulink by associating with a S-Function block.

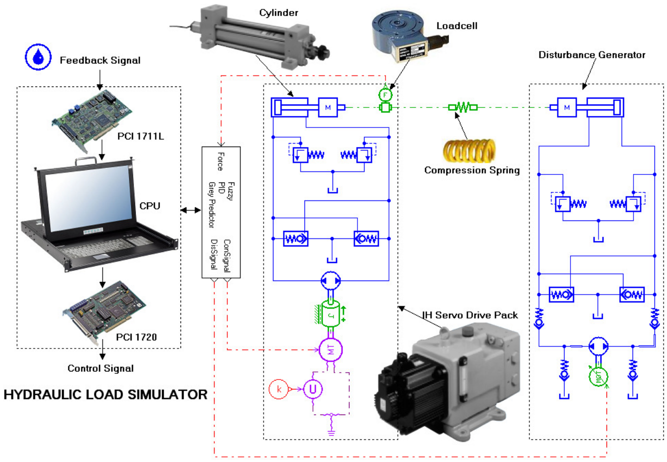


Fig. 12 AMESim model of the load simulator

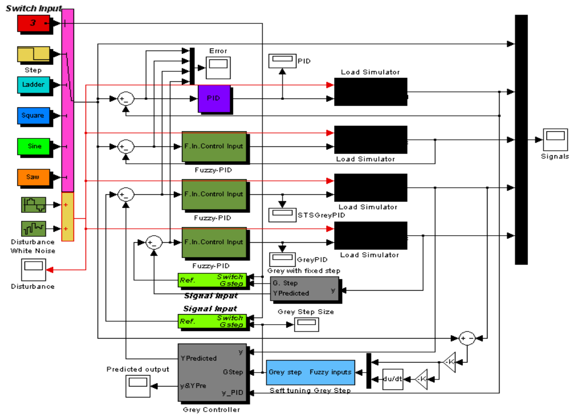


Fig. 13 Simulink model of hybrid actuator system with controller

4.2 Overall control system model

As described next, Simulink facilitates co-simulation with other simulation tools. MATLAB/Simulink is chosen as a common shell for building the simulation model due to its ability to support and interface seamlessly with the different DLLs provided from other tools. The DLL can be included in the Simulink environment in the form of a S-Function. All individual blocks of the simulation model are validated against real test data. Fig. 13 is the system with the controller built in Simulink.

Table 2. Setting parameters for AMESim models

Model parameters	Value	Meaning
AC Servo Motor	200	Power supply(Volt)
	2500	Revolution (rpm)
M (kg)	1000	Load
k (kN/m)	519	Environment stiffness
Sensor gain (1/N)	3	Force sensor signal
Cylinder parameters (mm)	63 x 35 x 150	Piston diameter x Rod diameter x Length of stroke
Relief Pressure (bar)	175	Relief valve cracking pressure

4.3 Simulation results

In this section, by using the above developed co-simulation platform, the states of the hydraulic system solved in AMESim are fed into the Simulink controller. The control signals from the controller are then fed back into the AMESim hydraulic model and the new states are solved. The setting parameters for the hybrid system model are obtained from real components as shown in Table 2, respectively. The simulations were done with sampling rate, 0.01 second, to check the system responses.

The comparison among the conventional PID, the fuzzy PID, the fixed step grey predictor – fuzzy PID and the self tuning step grey predictor – fuzzy PID controllers for load simulator model are done. Firstly, the same PID's coefficients are used for both control models. Fig. 14 shows the step responses of the system in cases of using different controller. The parameter values set for tradition PID ($K_p = 0.38$, $K_i = 0.003$ and $K_d = 0.051$) are derived from experiments with real model. The control performance of system using the fuzzy PID is better than using the conventional PID. However, when the self tuning step grey predictor – fuzzy PID is utilized, the control quality is the best not only about the rising time but also about the overshoot, settling time and steady error.

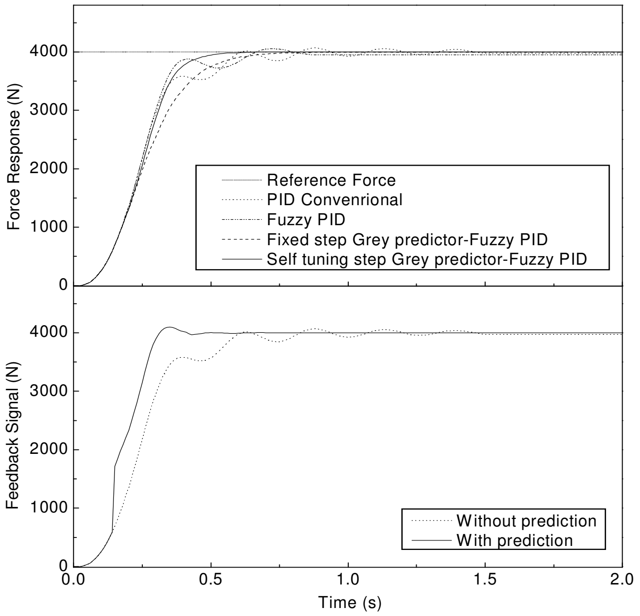


Fig. 14 The comparison of system responses - Simulation

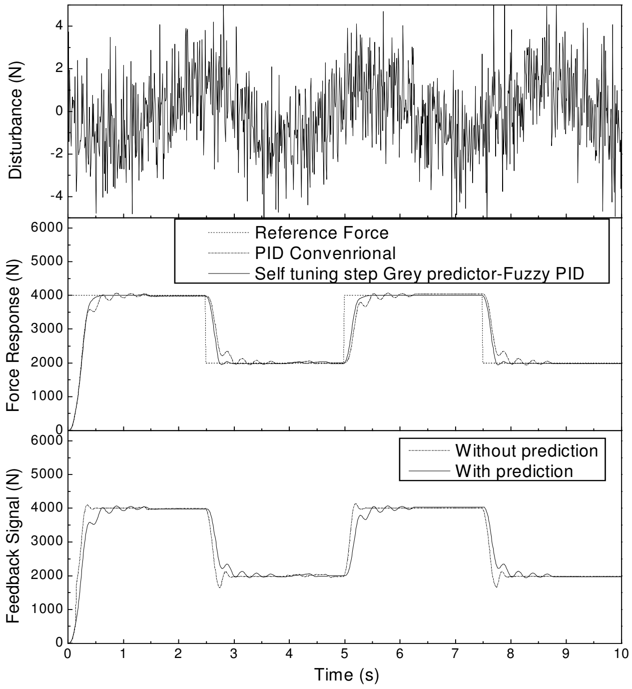


Fig. 15 System responses - Simulation

Secondly, to prove the effectiveness of the proposed controller, a disturbance scheme is included into the control diagram as shown in Fig. 13. The disturbance generated in this case can be expressed as below:

$$Dis(t) = A\sin(\omega t) + Rnd(t) \qquad (14)$$

where A and ω are amplitude and frequency parameters; *Rnd(t)* is the white noise signal.

To compare the control results for different set-point force including disturbance, the tracking square wave reference is investigated. Fig. 15 displays the output responses in the comparison. From the simulation test, it is obviously that the proposed controller achieves the best tracking response.

4.4 Experimental results

Experiments were also carried out to prove the effectiveness of the designed controller in the real system. The control algorithm is built in Simulink environment combined with Real-time Windows Target Toolbox of Matlab and connected to Advantage cards to control load simulator system. The sampling time was set to be 0.01s for all experiments. The noise signal performed in (14) is sent from the computer to the AC servo drive of the disturbance generation part by the DA converter (PCI 1720). Then the controlled AC servo motor with the hydraulic control circuit and piston are used to create the perturbation environment for the load simulator in testing the control performance (see Fig. 1). In order to compare the results for different set-point forces, the tracking multi-step forces are investigated (Fig. 16).

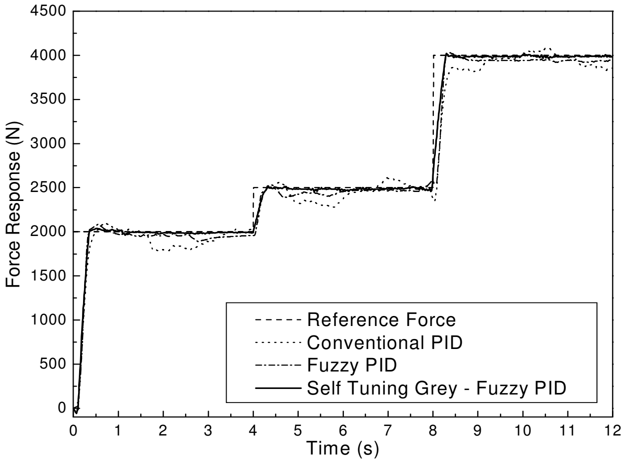


Fig. 16 Comparison of multi-step responses - Experiment

From all simulations and experimental results, it is clear that a good force regulation is realized in the case that a grey predictor with a fuzzy self-tuning step size to design a force controller is used.

5. CONCLUSIONS

This paper presents a new kind of hydraulic actuator – a compact energy-saving and low-noise hydraulic device which is combined as one with AC servo motor, piston pump, reservoir and hydraulic control circuit. A force control method using a fuzzy PID controller combined with a self tuning grey predictor is also designed and developed to apply for the hybrid system. As long as the parameters of the PID controller are tuned by a fuzzy set, a self tuning grey predictor is combined to obtain better performance and higher control precision in hydraulic load simulator system. By using a co-simulation method connecting between AMESim simulation software and Simulink toolbox, it was found that the proposed controller was able to satisfy the tracking performance specification, and disturbance attenuation requirement. This control method is effective not only for hydraulic actuators but also for other control systems.

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