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Performance Analysis of a Novel Independent Metering Valve System Using a Neural Network Fractional Order PID Controller Versus Conventional Optimal Tuning Methods

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***Abstract*— In this paper, an analysis of the tracking performance and energy efficiency of the novel independent metering valve (NIMV) system, utilizing an online tuning-based neural network for the FOPID controller, is conducted under variable load conditions and adverse factors such as noise, leakage, and throttling loss. Additionally, a comparison with conventional optimal tuning methods is made under the same conditions to evaluate the effectiveness of the proposed approach. Simulation results demonstrate that the proposed controller achieves not only high tracking accuracy but also significant energy savings.**

Keywords—Energy saving, hydraulic excavator, novel independent metering valve.

I. INTRODUCTION

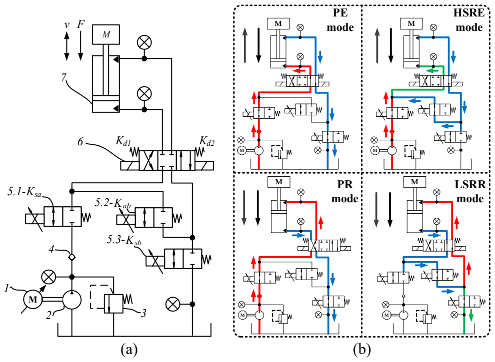
To address this issue of high energy consumption in the hydraulic excavator [1], the novel independent metering valve (NIMV) system has been developed [2, 3]. By using three 2/2-proportional valves and one 4/3 directional valve, the NIMV system can operate the boom excavator in four different working modes, optimizing energy consumption. Notably, the NIMV system allows the boom cylinder to be lowered using gravitational potential energy instead of energy from the pump, resulting in significant energy savings [4]. Nevertheless, negative factors such as noise, leakage, and throttling loss can affect the stability and performance of the NIMV system and should be addressed.

Our previous study proposed an auto-tuning method based on neural network control for a fractional-order proportional-integral-derivative (FOPID) controller to address the negative factors affecting the NIMV system [3]. However, the impact of variable load factors has not been considered, despite their influence on the system's accuracy. Moreover, comparisons with conventional optimal tuning methods, such as genetic algorithms (GA) and particle swarm optimization (PSO), have not been conducted, hindering a comprehensive evaluation of the proposed controller's effectiveness.

To address the problem, a study was conducted on the neural network- FOPID (NN-FOPID) controller under variable load conditions for the NIMV system. Additionally, the performance of the NN-FOPID controller was compared with GA-FOPID and PSO-FOPID controllers under the same conditions. To demonstrate the effectiveness of the proposed control method, a co-simulation was performed using the MATLAB/AMESim platforms. The simulation results showed that the NN-FOPID controller not only achieved high tracking precision but also demonstrated significant energy savings compared to the GA and PSO methods, with savings of up to 8.84% and 9.46%, respectively.

II. SYSTEM DESCRIPTION

The configuration of the NIMV system is shown in Fig. 1(a). For the application of the boom excavator, four operating modes have been developed based on load and design velocity conditions: power extension (PE) mode, power retraction (PR) mode, high-side regeneration extension (HSRE) mode, and low-side regeneration retraction (LSRR) mode, as shown Fig. 1(b). The PE and PR modes are the standard operating modes, while HSRE and LSRR are the regeneration modes [3].



(a) (b)

Fig. 1. (a) The configuration of the NIMV system. (b) Four working modes of the NIMV system.

III. CONTROL ALGORITHM

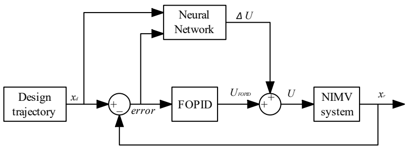


Fig. 2. The schematic of the NNFOPID controller.

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The schematic of the NN-FOPID controller is shown in Fig. 2, where the gradient descent (GD) method is used for weight updates in the neural network [3]. To balance computational efficiency with performance, a single hidden layer is chosen for the neural network.

The performance index function is defined as follows:

$$E_U(t)=\frac{1}{2}\left[\Delta U(t)-U(t)\right]^2=\frac{1}{2}e_U^2(t) \tag{1}$$

where ΔU is the output of neural networks and U is the output of the NN-FOPID controller after the update. The learning algorithm is established based on the GD method:

$$\boldsymbol{\Delta w}(t)=-\eta\frac{\partial E_U(t)}{\partial w(t)}=\eta e_U(t)\boldsymbol{h}(t) \tag{2}$$

where η is the learning rate and $\boldsymbol{h}=\left[h_j\right]$ with h_j is Gaussian function value h_j for net j, the h_j can be written as

$$h_j=\exp\left(-\frac{\left\|\boldsymbol{x}(t)-\boldsymbol{c}_j\right\|^2}{2b_j^2}\right) \tag{3}$$

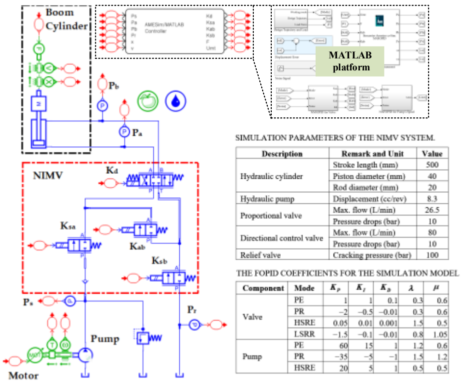
where input vector $\boldsymbol{x}=\left[x_i\right]$, $\boldsymbol{c}=\left[c_{ij}\right]$ represents the coordinate value of the center of the Gaussian function for the neural network net j corresponding to the $i-$th input, and the width b_j value of the Gaussian function. The weight update can be established as follows:

$$\boldsymbol{w}(t)=\boldsymbol{w}(t-1)+\boldsymbol{\Delta w}(t)+\alpha\left[\boldsymbol{w}(t-1)-\boldsymbol{w}(t-2)\right] \tag{4}$$

where α is the momentum factor. Finally, the output of neural networks can be defined as follows:

$$\Delta U=\boldsymbol{w}(t)^T\cdot\boldsymbol{h}(t) \tag{5}$$

IV. SIMULATION STUDY



SIMULATION PARAMETERS OF THE NIMV SYSTEM.

Description	Remark and Unit	Value
Hydraulic cylinder	Stroke length (mm)	500
	Piston diameter (mm)	40
	Rod diameter (mm)	20
Hydraulic pump	Displacement (cc/rev)	8.3
Proportional valve	Max. flow (L/min)	26.5
	Pressure drops (bar)	10
Directional control valve	Max. flow (L/min)	80
	Pressure drops (bar)	10
Relief valve	Cracking pressure (bar)	100

THE FOPID COEFFICIENTS FOR THE SIMULATION MODEL

Component	Mode	K_P	K_I	K_D	λ	μ
Valve	PE	1	1	0.1	0.3	0.6
	PR	−2	−0.5	−0.01	0.3	0.6
	HSRE	0.05	0.01	0.001	1.5	0.5
	LSRR	−1.5	−0.1	−0.01	0.8	1.05
Pump	PE	60	15	1	1.2	0.6
	PR	−35	−5	−1	1.5	1.2
	HSRE	20	5	1	0.5	0.5

Fig. 3. Co-simulation model and simulation parameters.

A. Simulation setup

To carry out the effectiveness of the proposed controller under variable load and negative factors, the co-simulation model of the NIMV system is built in MATLAB (2017b) and AMESim (2021) software, as shown in Fig 3. In addition, the comparison of the proposed controllers with the GA-FOPID and PSO-FOPID is conducted with two evaluation factors: tracking precision and energy saving.

B. Simulation Results

Fig. 4 presents the comparison of the tracking performance in the NIMV system in four working modes. From these results, the proposed controller not only achieves the highest tracking precision but also exhibits a faster convergence rate than the GA-FOPID and PSO-FOPID under variable load conditions, which is designed based on the switching mode of the NIMV system [2].

Additionally, the total energy consumption of the NN-FOPID, GA-FOPID, and PSO-FOPID controllers is 7.94 kJ, 8.71 kJ, and 8.77 kJ, respectively, as illustrated in Figure 5. These results highlight the superior energy saving capability of the proposed controller, achieving energy savings of up to 8.84% compared to GA-FOPID and 9.46% compared to PSO-FOPID.

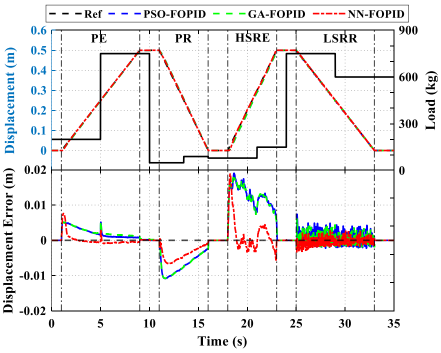


Fig. 4. The tracking performance of the NIMV system under variable load.

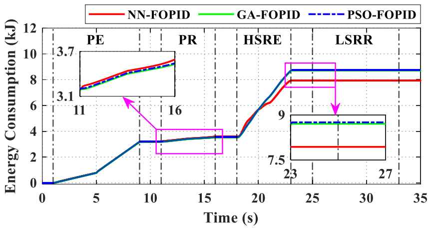


Fig. 5. Energy consumption of the NIMV system in the simulation.

V. CONCLUSIONS

This paper presented the investigation of the online tuning-based neural network for the FOPID controller under variable load conditions and negative factors that affect the NIMV system. Along with that, the comparison with the conventional optimal tuning methods such as GA and PSO was conducted in four working modes to accurately evaluate the performance of the proposed controller. Based on the simulation results, the proposed controller not only achieved the highest tracking precision but also used lower energy consumption, with a saving rate of 8.84% and 9.46%, respectively.

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