Application of RBF neural network and sliding mode control for a servo mechanical press*

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***Abstract*—Servo mechanical press is a complicated system with several transmission processes. The friction and other nonlinear factors are critical problems of servo press controlling. This paper focuses on the performance improvements of position tracking on servo press. In order to carry out the researches, first, the mathematic model which expresses the mechanical transmission processes is built to analyze the servo screw press system. Then an algorithm which combined neural network and fuzzy sliding mode (RBFFS) was proposed and applied on the position tracking of servo press. Finally, the simulation and experiment results indicate that the RBFFS control algorithm is effective and capable for servo press controlling.**

I. INTRODUCTION

Servo press provides flexible punch motions, which carry out an optimal stamping action that is programmed for production needs [1]. For a servo press, the punch stroke becomes adjustable, and this enhances productivity. In summary, high productivity, formability, low noise, long tool life, and energy saving can be achieved by applying the servo press on stamping operations. [2]

Servo mechanical press is a complex system. And nonlinear friction is a critical problem of it. This brings the difficulties in position controlling. Conventional proportional-integral-derivative (PID) controllers are commonly used due to their simplicity. This algorithm also applies in servo motor control. And this accomplishes the basic performance requirement of servo motors running. But the performance of servo motor deteriorates while the load of servo motor changes, especially nonlinear factors affects. While the servo motors equipped on presses, the inner position close-loop controller in driver may not achieve the demands of producers.

In the field of press controlling, several aspects have progressed. Some methods have been put forward, and have been proved to be effective way to solve the control problems. Some mechanical servo presses have coupling kinematic matters. Cheng-Ho Li and Pei-Lum Tso[3] present an iterative learning control method which used on a hybrid-driven servo press. Their experiment has worked on solving the kinematic model of servo press in controlling. Some studies focus on hydraulic press. D. Q. Truong and K. K. Ahn[4] proposed an online tuning fuzzy PID based on a robust extended Kalman filter and applied on the force controlling of hydraulic servo press machine, their experiment was proved effective on hydraulic servo press. Jian-ming Zheng, Sheng-dun Zhao and Shu-guo Wei [5] put forward a fuzzy PID controller which utilized on a switched reluctance motor direct drive volume control hydraulic press, position tracking control. Their researches present a new direction to solve the control problem on the nonlinear servo press. In the area of servo motor driven mechanical press control the researches are relatively less.

This paper focuses on the position tracking in a servo press prototype. Firstly, a servo screw mechanical press is introduced as the study object. In considering the nonlinear friction and the elastic deformation of synchronous belt, the dynamic model of this servo press was presented to express the servo press system. Secondly, a control algorithm which combined RBF neural network and fuzzy sliding mode controller was put forward to solve the nonlinearity and precision of servo mechanical presses controlling.

II. AC SERVO MECHANICAL PRESS

A. Structure

Servo mechanical presses usually build on the basis of conventional mechanical press. Instead of asynchronous motors and flywheels, the AC servo motor supplies better accuracy, and more energy conservation. As shown in Fig. 1, a typical servo screw press mainly consists of AC servo motor, redactor, pulley, screw, slider and mould. The rotary motion transits from left pulley to right pulley via a synchronous belt. Right pulley rotates the nut of screw. The screw connects the slider and upper mould. The rotary freedom of screw was restricted by leading guides.

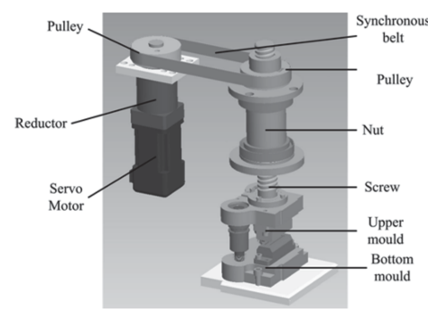

Figure 1. A typical transmission structure of servo screw press

While the AC servo motor works, the upper mould moves up and down, the punch motion acquired. The transmission

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system precision of this servo press was affected by nonlinearity, such as friction and the elastic deformation of belt, etc. Especially in low working velocity, the friction is the critical nonlinearity in press. Next, the friction was analyzed to deduce the mathematic model of servo press.

B. Frictions

Servo mechanical press is a complicated nonlinear system. Because of the big mass of moving parts, the nonlinearity of friction plays a critical role in the dynamic performance of servo press obviously. The nonlinear friction of slider mainly caused by the difference in static friction and the Stribeck effects [6]. The Stribeck friction model expresses the friction in low speed almost, and it can be described as follows

$$g(\dot{x}) = f_c + (f_s - f_c)\exp(-|\dot{x}|/v_s) \tag{1}$$

where, f_c is the coulomb friction;

v_s is the stribeck speed.

f_s is the static friction;

To avoid the discontinuity of friction force, the zero velocity interval is defined as $v_\varepsilon (0 < v_\varepsilon \le 1)$ which refers to the Karnopp [7] model. In $[-v_\varepsilon, v_\varepsilon]$, the friction is defined as a limited slope straight line. Then the friction functions can be reformed as (2).

$$F_f = \begin{cases} g(\dot{x})\operatorname{sgn}(\dot{x}) + f_v \dot{x} & |\dot{x}| > v_\varepsilon \\ \dfrac{f_s}{v_\varepsilon}\dot{x} & |\dot{x}| \le v_\varepsilon \end{cases} \tag{2}$$

where $g(\dot{x})$ is the Stribeck friction model which expressed in (1). It describes the friction at low speed in mechanical system. f_v is viscous friction; v_ξ is zero velocity threshold. F_f is the friction force between slider and the straight guide.

According to (2), the friction plot shows in Fig. 2

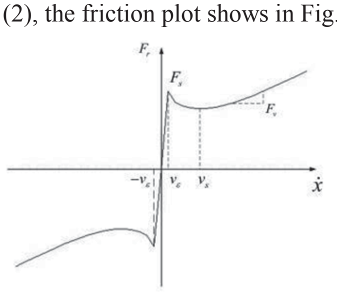

Figure 2. Friction function plot

C. Servo press system modeling

The servo press in Fig. 1 contains a number of driving processes. To facilitate the analysis, the influences of weak factors on transmission link were ignored. Then the servo mechanical press can be separated into driven part, actuator part and synchronous belt. Driven part consists of servo motor, redactor and synchronous pulley, the actuator part makes up of synchronous pulley, ball screw and mould. The two parts' pulleys are connected by synchronous belt. The simplified model is shown in Fig 3.

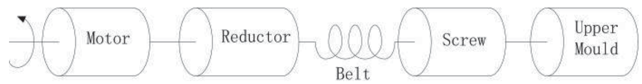

Figure 3. Simplified model of servo screw press

In driven part, the torque which generates from servo motor transmits to redactor firstly. Then the reducer increases the torque and spins the synchronous pulley. The dynamic function of driven part can be expressed as

$$\tau_i G = M_m \ddot{\theta}_m + V_m \dot{\theta}_m + f_{fc}(\dot{\theta}_m) + \tau_b \tag{3}$$

where M_m is the equivalent inertial coefficient of motor axis, redactor and pulley related to the input rotate speed.

V_m is the damping term

θ_m is the rotate angle of motor axis。

f_{fc} is the friction torque

τ_b is the torque which generates by synchronous belt.

In actuator part, the pulley is rotated by synchronous belt. The screw nut which restricts on the pulley also spins. The screw and upper mould possess the freedom in vertical direction. The dynamic function of actuator part is presented as

$$\tau_b = M_n \ddot{\theta}_n + V_n \dot{\theta}_n + \frac{m_n \ddot{x} + F_f + F}{2\pi} \tag{4}$$

where τ_b is the torque which generates by synchronous belt

M_n is the equivalent inertial coefficient of moving parts

V_n is the damping term

θ_n is the rotation angle of pulley。

F_f is the friction function based on Strebeck model

F is the external force on upper mould

The conversion function of upper mould displacement and pulley rotation angle is presented as

$$x = \frac{d\theta_n}{2\pi} \tag{5}$$

where d is the screw lead

Synchronous belt connecting the two parts in this servo press model is considered as elastomer. Its model can be described as

$$\tau_b = \left(\frac{\theta_m}{G} - \theta_n\right)K \tag{6}$$

G is the ratio of redactor.

K is the elasticity modulus of synchronous belt.

The servo mechanical press model is acquired by combining the (3)~(6). The diagram of servo screw press system is shown in Fig. 4.

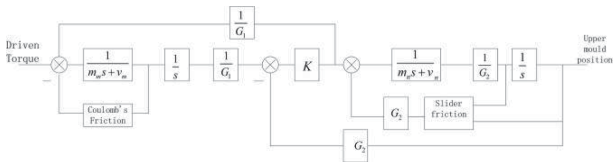

Figure 4. Model of servo screw press

In Fig. 4 the G_1 is the ratio of reducer, G_2 is the lead of screw.

III. NEURAL NETWORK & SLIDING MODE CONTROLLER DESIGN

A. Fuzzy sliding mode controller

Sliding mode controller is widely applied on robot control. It possesses the advantage of robustness. In this section, an algorithm is designed based on the fuzzy gain switch sliding mode control theory to accomplish the position tracking of servo screw press. The chattering phenomenon by this approach can be weakening compared to conventional sliding mode controller.

For the convenience of controller design, assume that the servo press dynamic model is simplified as following second-order deferential Equation.

$$\ddot{x}_s = f(x_s, \dot{x}_s) + bu + d_i \tag{7}$$

where,

x_s is the state vector of servo press model. b >0, d_i is the disturbance on system input.

To construct the error states. Assume that the signal of reference position is x_d. The reference position is smooth and has the second-order derivative almost everywhere. So the error state defined as follows:

$$e = x_d - x \tag{8}$$

$$\dot{e} = \dot{x}_d - \dot{x} \tag{9}$$

where, x is actual position of servo press upper mould.

In order to improve the position tracking precision and attain the good dynamic performance, the sliding mode surface defined as follows:

$$s = \delta e + \dot{e} \tag{10}$$

where, $\delta > 0$

The position error system (8), (9) can converge to zero in finite time while (10) was chosen as the sliding mode manifold and the control law is designed as follows:

$$u = \frac{1}{b}(-f(x,\dot{x}) + \ddot{x}_d + c\dot{e} + K(t)\operatorname{sgn}(s)) \tag{11}$$

where $K(t) = \max|d| + \eta$, and η >0.

When the lyapunov function $\dot{V} < 0$, the sliding mode controller exists and error system can converge. So the lyapunov function can be defined as

$$V = \frac{1}{2}s^2 \tag{12}$$

Then

$$\begin{aligned}\dot{V} &= s\dot{s} = s(\ddot{e} + c\dot{e}) = s(\ddot{x}_d - \ddot{x} + c\dot{e}) \\ &= s(\ddot{x}_d - f(x,\dot{x}) - bu - d - c\dot{e})\end{aligned} \tag{13}$$

$$\dot{V} = s(-K(t)\operatorname{sgn}(s) - d) = -K(t)|s| - ds \le -\eta|s| \tag{14}$$

In sliding mode controller, the switch gain $K(t)$ is the reason of chattering. $K(t)$ is used to compensate the disturbance d. For decreasing the chattering, $K(t)$ should be adjustable. Next, the fuzzy logic controller was utilized for the $K(t)$ adjustment.

From above, the input of fuzzy system defines as $s\dot{s}$, output defines as $\Delta K(t)$. The fuzzy sets defined as:

$$s\dot{s} = \{NB \quad NM \quad ZO \quad PM \quad PB\}$$

$$\Delta K(t) = \{NB \quad NM \quad ZO \quad PM \quad PB\} \tag{15}$$

where NB is the negative big, NM is the negative mid, ZO is zero, PM is the positive mid, PB is positive big.

The membership function of fuzzy sets shown in Fig. 5, 6.

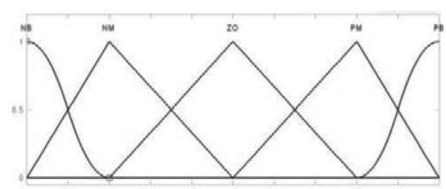

Figure 5. Membership function of input

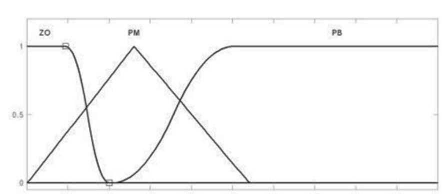

Figure 6. Membership function of output

Fuzzy rules are designed as below:

R1: if $s\dot{s}$ is PB then $\Delta K(t)$ is PB

R2: if $s\dot{s}$ is PM then $\Delta K(t)$ is PM

R3: if $s\dot{s}$ is ZO then $\Delta K(t)$ is ZO

R4: if $s\dot{s}$ is NM then $\Delta K(t)$ is NM

R5: if $s\dot{s}$ is NB then $\Delta K(t)$ is NB

The final sliding mode controller gain is

$$\widehat{K}(t) = G\Delta K \tag{16}$$

G is gain of output. Its value is up to experience.

Then the control law can be writes as

$$u = \frac{1}{b}(-f(x,\dot{x}) + \ddot{\theta}_d + c\dot{e} + \widehat{K}(t)\operatorname{sgn}(s)) \tag{17}$$

The mathematic model $f(x,\dot{x})$ is hard to obtain. Next, a algorithm based on RBF exponential convergence sliding mode control is proposed to accomplish the position tracking of servo press. In this algorithm, the sliding mode controller keeps the strong robustness of system, and the RBF neural network approaches the mathematic model which improves the control accuracy.

RBF neural network is proved to be a capable to approximate nonlinear system, and it was widely used among researchers, the algorithm of RBF neural network is:

$$f(x) = W^{*T}h(x) + \varepsilon \tag{18}$$

In (18), W^* is the ideal weight vector; ε is the error between real system output and neural network output. *h(x)* is the Gauss function:

$$h(x) = \exp\left(-\frac{\left\|x_i - c_j\right\|^2}{b_j^2}\right) \tag{19}$$

where, *x* is the input vector of neural network; *c* is the vector of center node; *b* is width vector; *j* is the number of node.

RBF neural network was used to approximate the target function $f(x,\dot{x})$ in control law (17). Then the control law can be writes as:

$$u = \frac{1}{b}(-\widehat{f}(x) + \ddot{\theta}_d + c\dot{e} + \widehat{K}(t)\operatorname{sgn}(s)) \tag{20}$$

where, $\hat{f}(x) = \hat{W}^T h(x)$ is the output of RBF neural network, the input of RBF neural network is $x = [x_1, x_2]^T$, x_1 is the position of servo press upper mould, x_2 is the velocity of servo press upper mould.

The weights update law of RBF neural network is as follow:

$$\dot{\hat{W}} = -\gamma s h(x) \tag{21}$$

The output error between actual $f(x,\dot{x})$ and neural network output $\hat{f}(x)$ is:

$$\begin{aligned} f(x) - \hat{f}(x) &= W^{*T}h(x) - \hat{W}^T h(x) - \varepsilon \\ &= \tilde{W}^T h(x) - \varepsilon \end{aligned} \tag{22}$$

where, $\tilde{W}^T = (W^* - \hat{W})^T$

When the Lyapunov function $\dot{V} < 0$, the error system can converge. So that the Lyapunov function can be defined as

$$V = \frac{1}{2}s^2 + \frac{1}{2\gamma}\tilde{W}^T\tilde{W} \tag{23}$$

where γ>0.

According to (10), $\dot{s}$ is obtained as:

$$\dot{s} = \delta\dot{e} + \ddot{x}_d - f(x) - u \tag{24}$$

As a result, the $\dot{V}$ is obtained from (14):

$$\dot{V} = s\dot{s} + \frac{1}{\gamma}\tilde{W}^T\dot{\tilde{W}} = s(\delta\dot{e} + \ddot{x}_d - f(x) - u) + \frac{1}{\gamma}\tilde{W}^T(-\dot{\hat{W}}) \tag{25}$$

The following equation is obtained from (10), (20), (22) (25)

$$\begin{aligned} \dot{V} &= s(\hat{f}(x) - f(x) - \widehat{K}(t)\operatorname{sgn}(s)) + \frac{1}{\gamma}\tilde{W}^T(-\dot{\hat{W}}) \\ &= s(-\tilde{W}^T h(x) - \varepsilon - \widehat{K}(t)\operatorname{sgn}(s)) + \frac{1}{\gamma}\tilde{W}^T(-\dot{\hat{W}}) \\ &= -s\varepsilon + \tilde{W}^T\left(-\frac{1}{\gamma}\dot{\hat{W}} - sh(x)\right) - \widehat{K}(t)\left|s\right| \\ &= -s\varepsilon - \widehat{K}(t)\left|s\right| \end{aligned} \tag{26}$$

The $\widehat{K}(t) > \left|\varepsilon_M\right|$, so that the Lyapunov function $\dot{V} < 0$.

This proved that the error state converges to zero in finite time. According to the above analysis, the block diagram of servo screw press control system can be obtained as shown in Fig. 7.

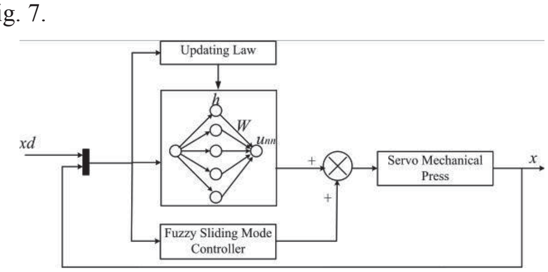

Figure 7. Structure of control system

IV. SIMULATION AND EXPERIMENT

In this section, the computer simulations are conducted to validate the feasibility of the proposed algorithm compare to fuzzy PID controllers. Simulation environment is Matlab/Simulink. The simulink model parameters are shown in Table I. Furthermore, experiments on the servo press with several test cases have been completed in laboratory to evaluate the effectiveness of the designed controller when applied to the press. The RBFFS control algorithm, which is used to control the output torque of servo motor, is build by the combination of Simulink Real-Time workshop, Advantech card and Googoltech motion control card. Fig.8 displays the testing machine. The displacement feedback sensor Renishaw RGH-41 grating scale as well as the computer control system are added to this servo press. The main parameters of servo mechanical press system are shown in Table II.

TABLE I. PARAMETERS OF SIMULATION SERVO PRESS

Parameters	Unit	Value
mm	Kgm2/s	1.53e-3
mn	Kgm2/s	4.01e-3
fc	N	2
fs	N	4
fv	N	3
vs	m/s2	0.5
vg	m/s2	0.01

TABLE II. PARAMETERS OF SERVO PRESS

Parameters	Unit	Value
Nominal force	kN	15
Motor power	kW	0.75
Motor nominal torque	Nm	2.3
Reductor ratio		12
Screw lead	mm	10
stroke	mm	130

The initial parameters of RBF neural network are set as follows δ=10, γ=1000, b=3.0, $W=[0.5\ 0.5\ 0.5\ 0.5\ 0.5]^T$, and

$$c=\begin{bmatrix}-1 & -0.5 & 0 & 0.5 & 1\\ -1 & -0.5 & 0 & 0.5 & 1\end{bmatrix}.$$

Figure 8. Servo press for experiment

The cosine curve with amplitude of 5mm and frequency of 1 rad/s was used to be the source signal in position tracking. Fig. 9 and 10 show the simulation results of fuzzy PID and RBFFS control tests.

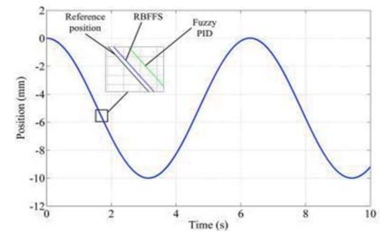

Figure 9. Simulation results of cosine curve tracking

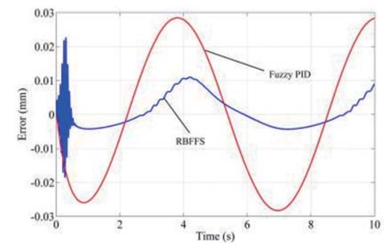

Figure 10. Simulation results of error in cosine curve tracking

From the results, it is clearly that in simulation, the tracking error by fuzzy PID controller become more oscillatory compared to RBFFS when the reference position is far from initial position. The maximum error of fuzzy PID controller reaches 0.03 mm. And the RBFFS is only 0.01 mm.

In RBFFS controller the error chatters at starting and lasting about 0.5 second. After more and more samples calculated in updating law, the RBF neural network became stable. The RBF neural network is well worked on providing the system equivalent output.

Experiments were executed to make the comparison among fuzzy PID, RBF controller. Fig. 11 and 12 are the comparison results. It is cleared that the position tracking of servo press machine using RBFFS controller was more stable than those of other controllers.

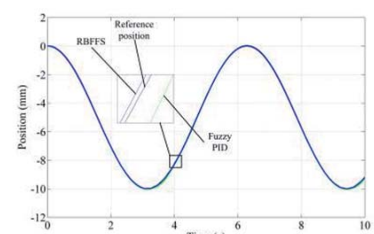

Figure 11. Experiment results of cosine curve tracking

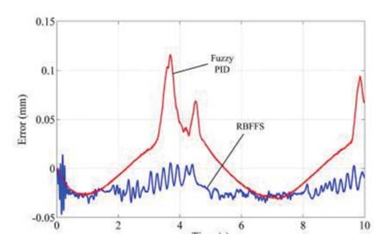

Figure 12. Experiment results of error in cosine curve tracking

The error in fuzzy PID is bigger, because the controller works by the error. With the bigger moving distance, the more error generates to compensate the force. The RBFFS has RBF to approximate the nominal model. It is more active to compensate the system than the fuzzy PID.

It is obvious that the RBFFS can distinctly improve the position tracking control precision compared with the fuzzy PID. It can adaptive the servo press model according to system inputs and outputs. And the self tuned sliding mode controller also enhances the robustness and decrease the chattering phenomenon in system. So the RBFFS can better satisfy the requirements of low speed position control of servo control for servo mechanical press.

V. Conclusion

This paper proposed the dynamic model of servo mechanical press. A control algorithm combined RBF neural network and fuzzy sliding mode was presented to apply on the servo mechanical press. The RBF neural network is used to approximate the model of servo press. And the sliding mode is to enhance the robustness of press controller. In the simulation and experiment, the position tracking algorithm was verified on a servo mechanical press. By the testing of referent motion of cosine curve, the algorithm proved to be an effective solution for servo mechanical press position tracking.

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