RESEARCH ON THE CONTACT PRESSURE CONTROL OF A DIE WEAR TESTER

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Abstract. In order to study the effect of the contact pressure on die wear during the stamping process of advanced high strength steels, this article analyzed the electro-hydraulic proportional control system on the contact pressure of a die wear tester, established the transfer function of the proportional-valve-controlled asymmetric hydraulic cylinder system, introduced PID control and simulated the control system in Simulink. The simulation results showed the control system responded fast and the errors were satisfactory. Then this article simulated the "equal" synchronous control strategy and the "master-slave" synchronous control strategy of the contact pressure and the wear displacement. The results showed that under the "master-slave" control, the deviation between the actual pressure and the target pressure was less and the control effect was better.

Keywords: Die Wear Tester, Contact Pressure, Electro-hydraulic Proportional Control, Synchronous Control.

1. INTRODUCTION

The application of advanced high strength steels (AHSS) in automobile shell forming, which achieves the same strength with thinner plates, is an important measure for lightweighting of automobile, energy saving and emission reduction. But the increase of sheet strength causes serious die wear problems during the stamping process, which results in surface quality problems of the sheet [1]. Therefore, a die wear tester was developed to research the die wear situations during the AHSS stamping process by simulating stamping conditions, which would help to select appropriate kinds of die material and predict the die life.

Among those conditions of stamping, the changes of the contact pressure between the sheet and the die have an important influence on the wear and the fatigue of the die. The typical change curves of the contact pressure with the stamping stroke are shown in Figure 1, it can be seen that there is a transient state and a steady state in U-shaped part stamping process. In the transient state, the contact is not close enough, so the pressure is high and changes drastically, the peak value has a significant effect on the wear situation during the stamping process [2]; in the steady state, the die and the sheet attaches closely, so the pressure becomes lower and stable. Thus, how to simulate the dramatic changes of the contact pressure with the stamping stroke correctly is the sticking point to develop the die wear tester.

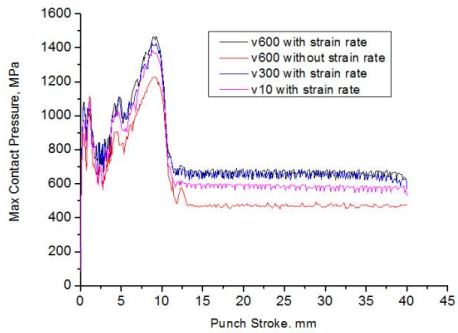


FIGURE 1. The change curves of the contact pressure with the stamping stroke

In view of the feature that contact pressure changed drastically with the stamping stroke, so in the tester, an electro-hydraulic proportional control system was adopted to control the pressure, which had high control precision, high power density, fast dynamic responses and suitable costs [3]. But the dead zone and the flow nonlinearity of the proportional valve have a great influence on the system control characteristics. Therefore, the choice of control methods and control strategies is the key to realize the contact pressure control and the synchronization of the contact pressure and the wear displacement.

2. THE COMPOSITION OF THE DIE WEAR TESTER AND THE WORKING PRINCIPLE

After detailed analysis of the various conditions during the stamping process, as shown in Figure 2, an electro-hydraulic system was designed as the composition of the wear tester. The hydraulic schematic diagram is shown in Figure 3.

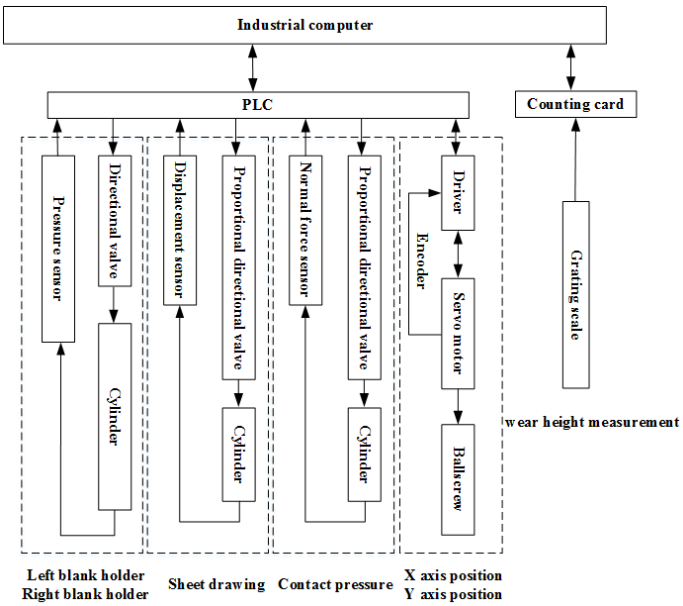


FIGURE 2. The composition of the wear tester electro-hydraulic system

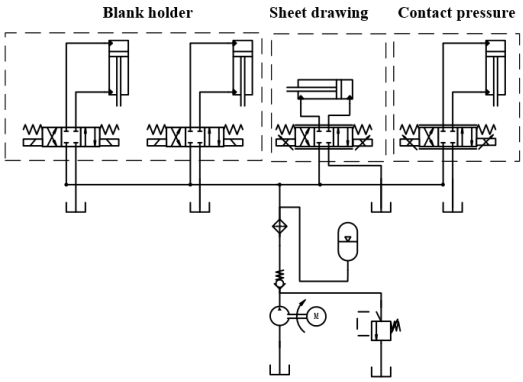


FIGURE 3. The hydraulic schematic diagram

The blank holder is to fix the plate on the worktable. When the plate is put on the worktable, there is a hydraulic cylinder above each side of the plate. The PLC outputs control signals to the directional valves, changes the oil circuit and makes the hydraulic cylinders moving downward. The plate is fixed. The oil pressure is measured back to the PLC by pressure sensors. When the pressure reaches the pre-set value, the valves return to the median position. The part of the right blank holder cylinder is separated from the left part and has slide rails underside. The piston rod end of the drawing cylinder on this side is connected with the right part. The PLC outputs analog voltage to the proportional directional valve. The size and the direction of this voltage control the speed and the direction of the drawing cylinder. The movement position is input to the PLC by a displacement sensor. After reaching the pre-set position, the PLC controls the cylinder to stop moving.

The movement of a hydraulic cylinder controls the contact pressure. The cylinder is installed vertically and there is a normal force sensor on the underside. The die grinding head is at the bottom. When wearing, the grinding head contacts with the plate. The PLC outputs analog voltage to the proportional directional valve to control the vertical motion of the cylinder, which changes the contact pressure between the grinding head and the plate. The normal force is returned to the PLC by the force sensor. The servo motors and ballscrews complete the horizontal movement of the grinding head relative to the plate along X-axis and Y-axis. The position control module of the PLC controls the horizontal movement.

After moving a pre-set distance with pre-set conditions, the grating scale is used to measure the wear height. It converts the height to a number of pulses, which will be counted by a counting card. The upper computer software runs on the industrial computer. The computer sends operation information to the PLC through the Ethernet, displays sensor information and motion status collected by the PLC in the software interface and converts the count value of the counting card to the actual wear height.
By setting different contact pressures and wear speeds, researchers can study the effect of the pressures and the speeds on the wear situation. By changing grinding heads made of different materials, researchers can compare the wear resistance of different materials. By simulating the actual conditions during the stamping process, researchers can predict the die life and direct the production.

3. MODELLING OF THE ELECTRO-HYDRAULIC PROPORTIONAL CONTROL SYSTEM ON CONTACT PRESSURE AND CONTROL STRATEGIES

Considering that the contact pressure between the plate and the die has a great influence on the wear situation and the pressure changes drastically during the stamping process, it is necessary to model the oil circuit about the contact pressure and put forward reasonable control strategies.

3.1 Modelling of the Electro-hydraulic Proportional Control System on Contact Pressure

The oil circuit about the contact pressure can be seen as a proportional-valve-controlled asymmetric hydraulic cylinder system. The external voltage input determines the displacement of the valve core, which determines the displacement of the cylinder and the contact pressure. In the system modelling, when the hydraulic natural frequency of the hydraulic power mechanism is low, the transfer function can be considered as a first-order object. When the hydraulic natural frequency is high, the transfer function can be seen as a second-order object. In the article, the proportional valve was expressed as a first-order object. The transfer function between the valve core displacement (X) and the voltage input (U) is:

$$\frac{X(s)}{U(s)} = \frac{1/K_x}{T_v s + 1} \tag{1}$$

Here K_x is the proportional feedback gain of the valve core displacement, T_v is the equivalent time constant of the valve.
Then the valve-controlled asymmetric hydraulic cylinder system shown in Figure 4 was analyzed.

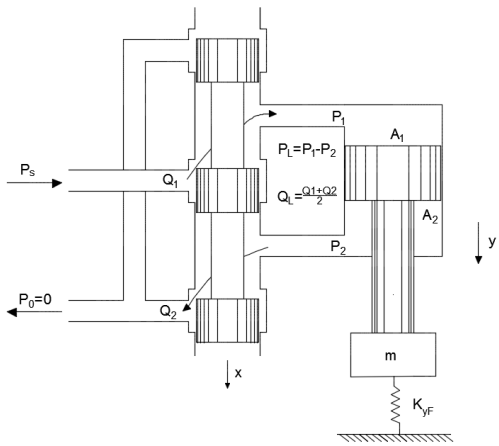


FIGURE 4. The schematic diagram of the valve-controlled asymmetric hydraulic cylinder system

The hypotheses were assumed before analyzing the system [4]:
(1) The valve was an ideal zero-opening four-port slide valve and four throttle windows were matching and symmetrical.
(2) The flow at theses throttle windows was turbulent.
(3) The supply pressure (P_s) was constant and the return pressure (P_0) was zero.
(4) The valve had ideal response ability, which meant that the flow change caused by the valve core displacement and the change of valve pressure drop completed instantaneously.

Based on these hypotheses, the article used the valve flow equation to establish the relationship between the valve flow (Q_L), the valve core displacement (X) and the load pressure (P_L). It is as follows:

$$Q_L = K_q X - K_c P_L \tag{2}$$

where K_q is the flow gain and K_c is the flow-pressure coefficient.
Then established the relationship between the proportional valve and the hydraulic cylinder by the flow equation of the hydraulic cylinder:

$$Q_L = C_t P_L + \frac{V_e \dot{P}_L}{4\beta_e} + A_{me}\dot{y} \tag{3}$$

Here $\dot{y}$ represents the piston velocity, C_t is the total leakage coefficient of the cylinder, V_e denotes the equivalent volume of the cylinder, β_e is the effective volume elastic modulus and A_{me} represents the average piston area. V_e was computed by equation (4) and A_{me} was computed by equation (5).

$$V_e = \frac{(1+\eta^3)A_1}{1+\eta^2} L = A_e L \tag{4}$$

$$A_{me} = \frac{A_1 + A_2}{2} \tag{5}$$

A_1 represents the area of the piston no-rod side and A_2 represents the area of the piston rod side. η is the flow ratio of the left and the right cavities, its value is $\frac{A_2}{A_1}$, L stands for the maximum stroke of the cylinder and A_e is the equivalent working area of the cylinder.
In order to find the relationship between the piston rod displacement and the voltage input, the load pressure equation of the cylinder[5] (the relationship between the load pressure, the piston rod displacement (y), the disc spring elastic force (F_d) and the external disturbing force (f)) was introduced:

$$P_L = (\mathrm{M}\ddot{y} + F_d + f - f_{ad})/A_e \tag{6}$$

Here M represents the total mass of the piston and the load, f_{ad} is an intermediate quantity produced in the calculation, it could be expressed as follows:

$$f_{ad} = \begin{cases} \dfrac{A_1\eta^2(1-\eta)P_s}{1+\eta^2} & \dot{y} \geq 0 \\ \dfrac{A_1(1-\eta)P_s}{1+\eta^2} & \dot{y} < 0 \end{cases} \tag{2}$$

The end of the piston is equipped with a normal force sensor, several series disc springs and a grinding head. The buffer springs can make the displacement greater under the same contact pressure, which helps to adjust the pressure. Considering that the mass, the velocity and the acceleration of the grinding head is relatively small, the article thinks the contact force (F) equals to the disc spring elastic force:

$$F = F_d = K_{yF} y_r \tag{8}$$

Where K_{yF} is the elastic coefficient of the disc springs, y_r is the piston rod displacement relative to the plate after that the springs begins to be compressed, which is determined by the piston rod displacement and the plate fluctuation (y_s):

$$\mathrm{y}_r = y - y_s \tag{9}$$

By uniting these equations, the transfer function of the proportional-valve-controlled asymmetric hydraulic cylinder system was obtained as follows:

$$
\mathrm{Y(s)} = \frac{\dfrac{K_q}{A_{me}}\dfrac{1}{K_x(T_v s+1)}U(s) + \left(\dfrac{K_c + C_t + \dfrac{V_e s}{4\beta_e}}{A_{me}A_e}\right)\left[K_{yF}Y_s(s) - f(s) + f_{ad}(s)\right]}{\left[\left(\dfrac{K_c + C_t + \dfrac{V_e s}{4\beta_e}}{A_{me}A_e}\right)\left(Ms^2 + K_{yF}\right) + s\right]}
$$

$$
= \frac{\dfrac{K_q}{A_{me}}\dfrac{1}{K_x(T_v s+1)}U(s) + \dfrac{K_{ce}}{A_e A_{me}}\left(\dfrac{V_e}{4\beta_e K_{ce}}s + 1\right)\left[K_{yF}Y_s(s) - \boldsymbol{f}(s) + f_{ad}(s)\right]}{\dfrac{V_e M}{4A_{me}A_e\beta_e}s^3 + \dfrac{K_{ce}M}{A_{me}A_e}s^2 + \left(\dfrac{V_e K_{yF}}{4A_{me}A_e\beta_e} + 1\right)s + \dfrac{K_{ce}K_{yF}}{A_{me}A_e}} \tag{10}
$$

Where $K_{ce} = K_c + C_t$.
According to equation (10), the block diagram of the transfer function is shown in Figure 5.

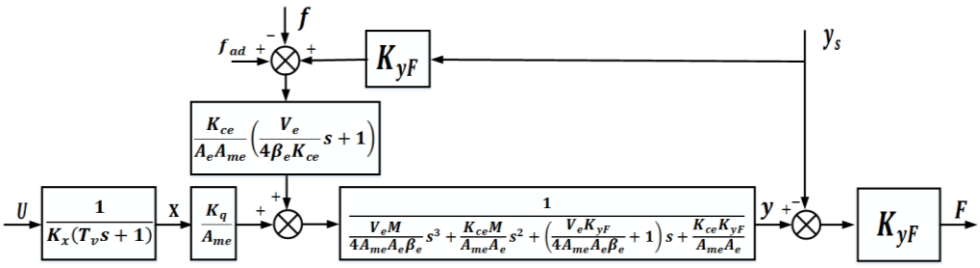


FIGURE 5. The transfer function of the contact pressure execution system

3.2 The Contact Pressure Control and the Synchronous Control

3.2.1 The PID Control of the Contact Pressure Execution System

Considering that PID control was widely used in the engineering, PID control was adopted to control the contact pressure. The control block diagram is shown in Figure 6.

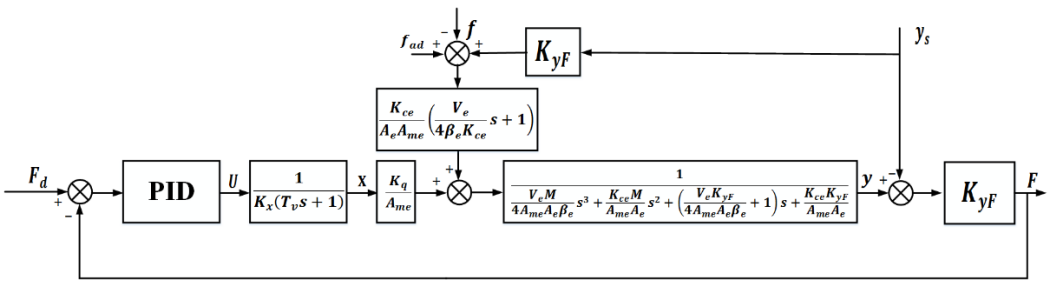


FIGURE 6. The transfer function of the contact pressure PID control system

F_d represents the target normal force.
In order to simulate and verify the control system, the values of these parameters were assigned as table 1.

TABLE 1. The parameters table of the electro-hydraulic proportional control system

Parameters	Meanings	Values	Units
K_x	Proportional feedback gain of valve core displacement	1.2	V/m
T_v	Equivalent time constant of the valve	0.012	s
K_q	Flow gain of the valve	0.0171	$(m^3/s)/m$
A_{me}	Average piston area	0.1231	m^2
K_{ce}	Total flow-pressure coefficient	5.86×10^{-8}	$m^3/(s \cdot Pa)$
A_e	Equivalent working area of the cylinder	0.1341	m^2
V_e	Equivalent volume of the cylinder	0.0262	m^3
β_e	Effective volume elastic modulus	6.5×10^8	Pa
K_{yF}	Elastic coefficient of the disc springs	6.47×10^5	N/m

CONTINUED TABLE 1

Parameters	Meanings	Values	Units
M	Total mass of the piston and the load	20	kg
A_1	Area of the piston no-rod side	0.1407	m^2
A_2	Area of the piston rod side	0.1055	m^2
η	Flow ratio of the left and the right cavities	0.75	1
P_s	Supply pressure	1	MPa

The PID control system of the contact pressure in Simulink is shown in Figure 7.

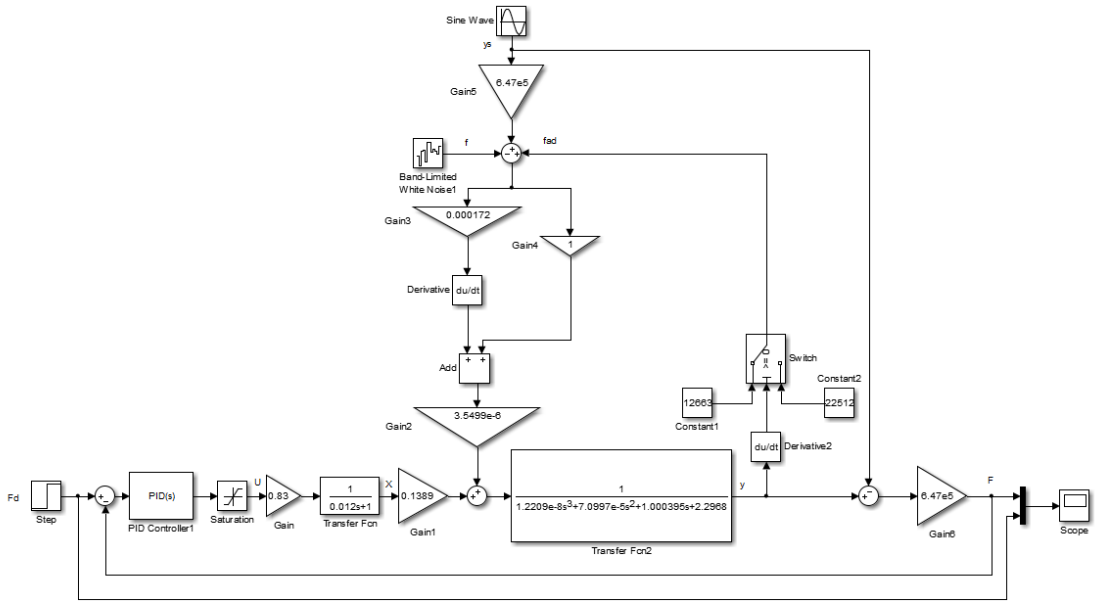
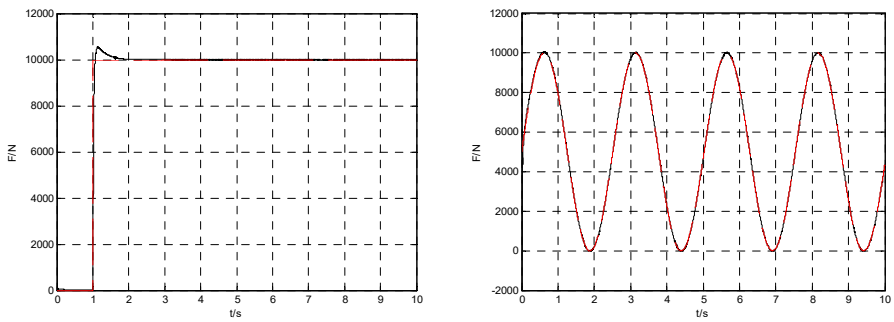


FIGURE 7. The simulation model of the contact pressure PID control system

The target normal force was set to a step signal with a steady value of 10000N or a sinusoidal signal with an amplitude of 5000N, the external disturbing force f was a white-noise signal and the plate fluctuation (y_s) was a sinusoidal signal.
The simulation results are shown in Figure 8 (the dotted line is the target force; the solid line is the actual force).



(a) Step signal response curve **(b)** Sinusoidal signal response curve

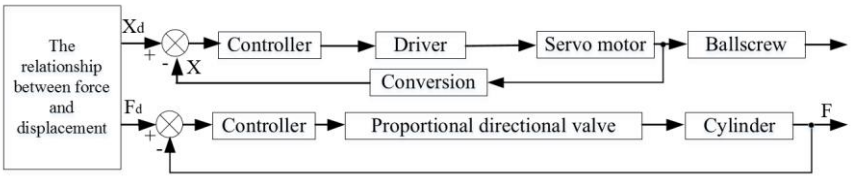
FIGURE 8. The simulation results of the contact pressure PID control system

It can be seen from Figure 8 that the step response has a certain overshoot, which means the system responds fast, and stabilizes within a certain range around the target pressure. The sinusoidal signal response tells that the follow effect of the system is great.

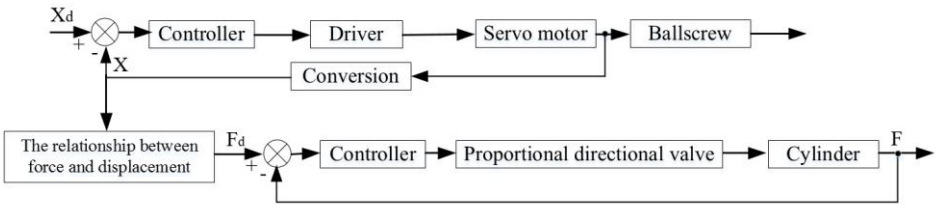
3.2.2 The Synchronous Control Strategies of the Contact Pressure and the Wear Displacement

The "equal" control and the "master-slave" control are two kinds of basic synchronous control strategies [6]. Under the "equal" control, every execution part tracks its own pre-set aim value to achieve the synchronization. Under the "master-slave" control, the output of a "master" execution part is considered as an ideal output, other parts track this output to

achieve the synchronization. These two synchronous control strategies of the contact pressure and the wear displacement are shown in Figure 9.



(a) The schematic diagram of the "equal" control



(b) The schematic diagram of the "master-slave" control

FIGURE 9. The schematic diagrams of these two synchronous control strategies

Under the "equal" control, this article set the target normal force and the target displacement corresponding to the same time based on the known relationship between the contact pressure and the stamping stroke. The force and the displacement were controlled separately. Under the "master-slave" control, because of the pressure fluctuation during the stamping process, the same force may correspond to different displacements. So this article took the displacement control as the ideal output and computed the pre-set force based on the actual displacement, which directed the force control later.

In order to compare the control effect of these two control strategies, simulations were carried out in Simulink. Among these simulations, a AC servo motor position control system was modelled to represent the displacement control system referring to the modelling process in the article [7]. The ballscrew pitch is 10mm. The model is shown in Figure 10, X_d represents the target position and X represents the actual position.

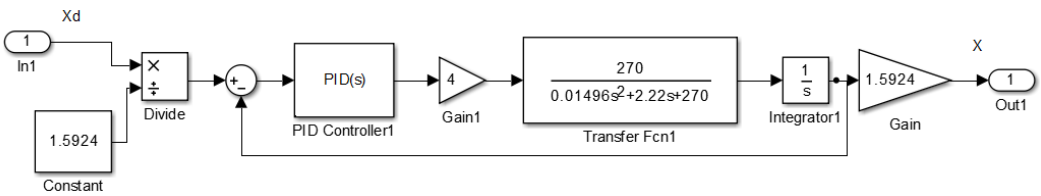


FIGURE 10. The position control system

The horizontal velocity was set as 5mm/s. The relationship between the force and the displacement is shown in Figure 11.

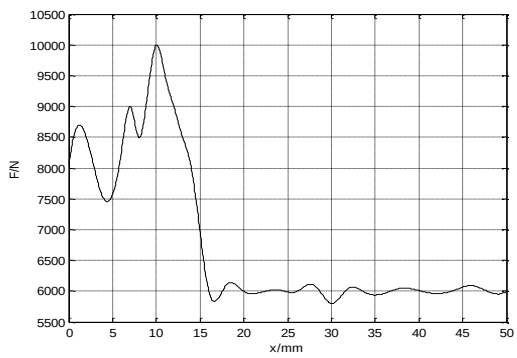


FIGURE 11. The change curve of the normal force with the displacement

The "equal" control simulation model is shown in Figure 12. MATLAB Function is the relationship in Figure 11.

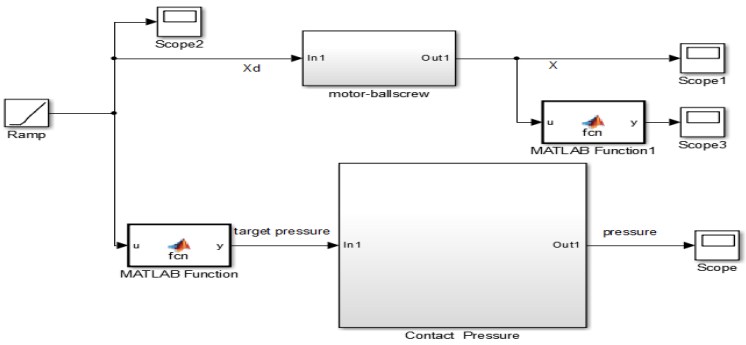
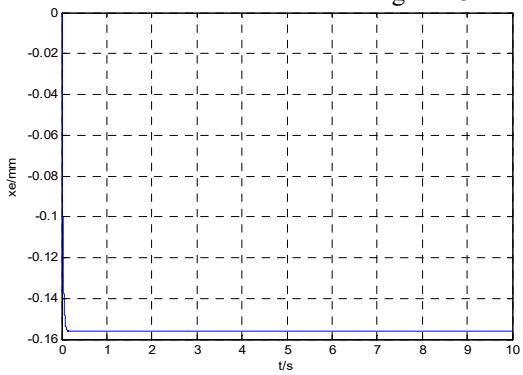
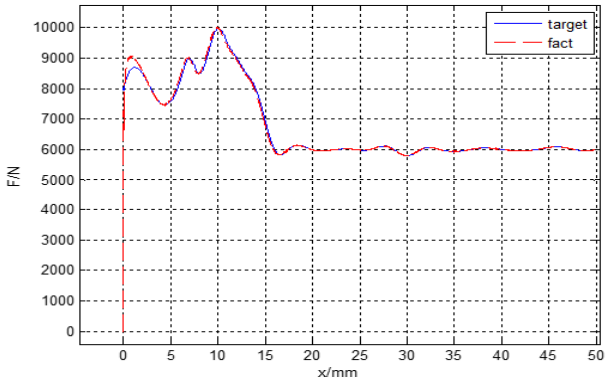


FIGURE 12. The "equal" control simulation model

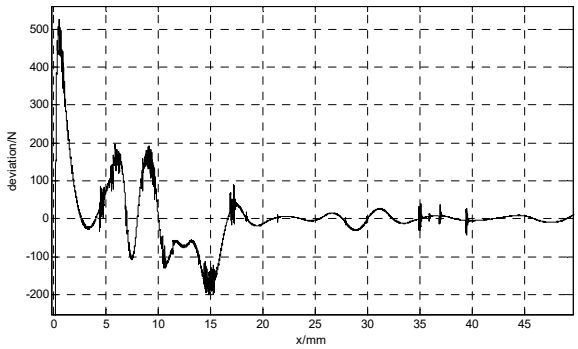
The simulation results can be seen in Figure 13.



(a) The displacement error under the "equal" control



(b) The comparison between the target force and the actual force under the "equal" control



(c) The force error under the "equal" control

FIGURE 13. The "equal" control simulation results

The "master-slave" control simulation model is shown in Figure 14.

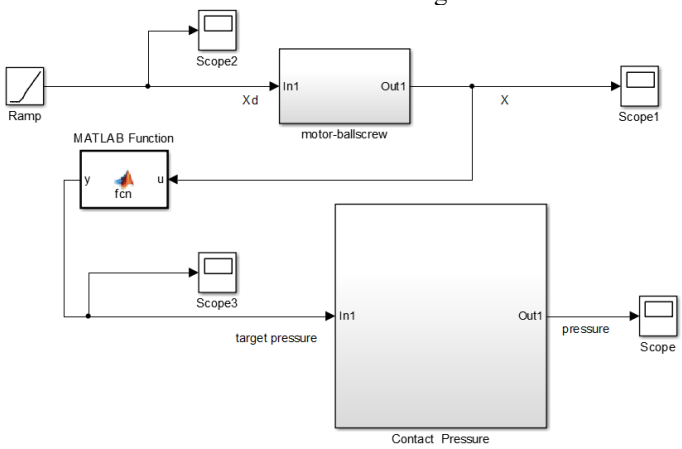
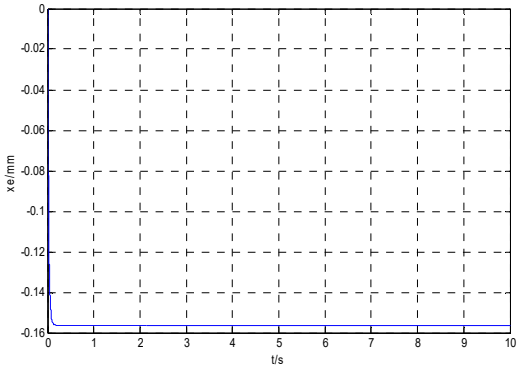
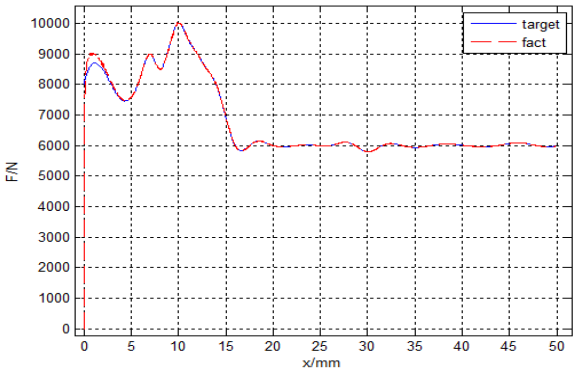


FIGURE 14. The "mater-slave" control simulation model

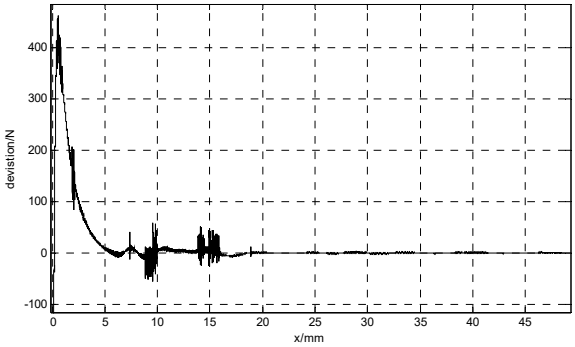
The simulation results are as follows:



(a) The displacement error under the "master-slave" control



(b) The comparison between the target force and the actual force under the "master-slave" control



(c) The force error under the "master-slave" control

FIGURE 13. The "master-slave" control simulation results

It can be seen from Fig.13 (a) and Fig.15 (a) that the displacement control results under these two control strategies are almost identical. The maximum dynamic error between the actual displacement and the target displacement is 0.1563mm.

Fig.13 (b) and Fig.15 (b) displays that these two control strategies did not adjust in time at the beginning. But after x=5mm, the adjustment improved greatly.

Fig.13 (c) and Fig.15 (c) shows that the overshoot under the "master-slave" control is lower and after the overshoot, the errors under the "master-slave" control are obviously less than those errors under the "equal" control. Therefore, the "master-slave" control strategy was chosen to the synchronous control of the contact pressure and the wear displacement.

4. CONCLUSIONS

The die wear tester designed in this article simulates the important conditions of the stamping process, which achieve the blank holder, the plate drawing and the contact pressure control by hydraulic valves and cylinders and achieve horizontal movement by servo motors and ballscrews. Considering that the contact pressure during the stamping process changed drastically and had an important influence on the die wear, the article focused on the modelling and the computer simulation of the contact pressure electro-hydraulic proportional PID control system. The simulation results show that the response is fast and the errors are satisfactory.

In view of the fact that the correspondence relationship between the contact pressure and the wear displacement could influence the wear rate, this article studied the synchronous control strategies of the pressure and the displacement. The comparison of the simulation results under the "equal" control and the "master-slave" control show that under the "master-slave" control which sees the displacement control result as the ideal output, the errors between the actual normal force and the pre-set normal force are smaller. Therefore, the "master-slave" control is more suitable for the synchronous control.

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