Hydraulic control system of mechanical energy stored type powder high velocity compaction machine

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Abstract. An automatic control scheme of spring energy storage by hydraulic control of spring compression is presented and implemented in this paper to improve the automation level, control accuracy and production efficiency of the existing HVC machine with mechanical energy storage type. The hydraulic system, servo system, and PLC codes are developed. The PID control optimization is applied for the control error accuracy of the machine. The transfer function is derived, and the genetic algorithm is used to optimize the PID parameters. The control scheme is implemented in the updated machine. The experimental results of iron powder HVC are in agreement with the predicted and calculated values. The reliability and validity of the automatic control scheme is verified. The research facilitates the industrial application of this kind of equipment.

1. Introduction

High Velocity Compaction (HVC) can effectively improve the densification, product performance and production efficiency of powder compacts. Because of its advantages of high impact speed, low cost, low elastic aftereffect and low demoulding force comparing with traditional pressing methods\cite{1}, HVC has been widely used\cite{2-4} and further developed recently\cite{5-7}. The HVC research of iron-, aluminum- and magnetic-based materials indicate that the impact velocity and energy have a critical influence on compact densification during HVC\cite{7-9}.

The energy storage methods of HVC equipment include hydraulic, gravity, pneumatic, electromagnetic, and chemical forms\cite{10-13}. Mechanical energy storage machine\cite{14} employs hydraulic pressure to drive mechanical spring, which provides energy and push the hammer to compress powder. Guan\cite{14} carried out the upsetting test of copper pillars on the test machine. The rationality of the machine design was verified by comparing the experimental data. Subsequently, 316L stainless steel powder was tested on a test machine. The maximum compact density of the sample was 7.84 g/cm\textsuperscript{3}, which was higher than 7.336 g/cm\textsuperscript{3} of the sample produced by the HYP35-7 machine of Nanjing Hilton Precision Machinery Co., Ltd.\cite{15}. In addition, the results of other experiments\cite{7-10}, demonstrate that the test machine has good forming ability and can meet the research needs. However, because the impact energy is controlled by manually adjusting the spring compression, the automation level, the control accuracy and the production efficiency of the machine needs to be improved. Then the test machine can’t be applied in industrial automation production.

Based on the existing test machine, an automatic control scheme of spring energy storage by hydraulic control of spring compression is presented and implemented in this paper to facilitate industrial application of mechanical energy storage HVC machine.
2. Hydraulic control method

The hydraulic system mainly consists of three hydraulic cylinders, three reversing valves, eight buttons and a Mitsubishi touch screen. The hydraulic servo control frame is shown in Figure 1. After setting parameters on the PLC, the feedback signal and the input signal of the force sensor and the displacement sensor are compared and amplified on the PLC, and then transmitted to the reversing valve to control the opening size of the valve core. Thereby, the amount of hydraulic oil in and out of the cylinder can be adjusted to implement the control of the spring displacement. The spring force signal is read by a pressure sensor installed in the three-way pipe of the inlet of the hollow hydraulic cylinder, and the spring displacement signal is read by a displacement sensor mounted on the hydraulic cylinder. The entire system is a closed-loop control system.

![Figure 1. Frame of hydraulic control system](image)

3. Mathematical model of control system

According to the energy control error of the closed-loop control system, a mathematical model is established to solve the transfer function of the system. The proposed hydraulic control system drives the reversing valve core according to the PLC signal, and then controls the movement of the piston rod of the hollow hydraulic cylinder to realize the automatic control of energy storage. The transfer functions are obtained as follows:\[17]\:

\[
G(s) = \frac{K_{sv}A_pK_e}{K_LK_{ec}} \left[ \left( \frac{s^2}{w_{sv}^2} + \frac{2\xi_{sv}}{w_{sv}} s + 1 \right) \left( \frac{s^2}{w_0^2} + 1 \right) \left( \frac{s^2}{w_0^2} + \frac{2\delta_0}{w_0} s + 1 \right) \right]^{-1}
\]

(1)

Where \(w_{sv}\) is the natural frequency of the reversing valve; \(\xi_{sv}\) is the damping ratio of the reversing valve; \(K_{sv}\) is the gain; \(A_p\) is the effective area of hydraulic cylinder; \(w_0\) is the natural frequency of hydraulic cylinder; \(\delta_0\) is the damping ratio; \(K_{ec}\) is the flow pressure coefficient; \(K_L\) is the gain coefficient. For the displacement sensor, the response speed of the hydraulic cylinder is lower than the response speed of wire encoder pulse, so the encoder link can be regarded as a proportional link, expressed in \(K_c\). The link of the pressure sensor is approximate proportional link for its high frequency bandwidth, expressed in \(K_f\).

The analysis of formula (1) shows that the type 0 system is difficult to meet the fast and quasi-stable characteristics when the signal input. For step function input, the accuracy and rapidity of closed-loop system can be satisfied, but the system may be unstable and oscillate. Hence, the PID module is added to the system to optimize the system control.

3.1. Modeling of PID control for hydraulic system

The AMESim software is used in modeling and simulation. The relationship between the output signal and the input signal is as follow:
\[ v = K_p u + K_i \int_{t_0}^{t} u dt + K_d \frac{\partial u}{\partial t} \]  \hspace{1cm} (2)

Where \( v \) is the output signal; \( u \) is the input signal; \( K_p \) is the scale factor; \( K_i \) is the integral coefficient; \( K_d \) is the differential coefficient; \( t \) is the first order lag time constant.

3.2. Hydraulic control system modeling

The hydraulic cylinder model is created and imported into the mechanical Adams module of spring control, and the integrated model of the hydraulic control system for spring energy storage is established by using AMESim software, as shown in Figure 2.

![Integrated AMESim model of energy control](image)

A series of simulations run one by one in sequence after initializing by different groups of parameters. The genetic algorithm is applied to optimize the PID parameters. The range of PID parameters is determined by AMESim batch processing function. The range of the proportional part \( K_p \) is set (10, 20, 50, 100, 200); \( K_i \) and \( K_d \) are set to 0 and signal 1 is set 1000 J. Then the influence of the parameters variation on the control performance of the system is observed and analyzed.

In the design exploration module of AMESim, the experimental design tool DOE is employed to analyze the parameters and obtain the relationship between the response and the input, and the genetic algorithm in optimization module is used to optimize the PID parameter. Setting the optimized population size 30, the replication probability 0.8, and the mutation probability 0.05, the PID parameters obtained after 36 generations evolution are \( K_p=105.01 \), \( K_i=0.135 \) and \( K_d=0.05 \). Spring deformations calculated using optimized PID parameters are shown in Figure 3.

![Spring displacement curve after optimization](image)
4. HVC experiment and validation of control system

4.1. Experimental method and device
The experimental material is water atomized iron powder. Two groups of experiments, the energy and the stroke validation tests were carried out. The energy values in each test were set at 200, 500, 800, 1100, 1400, 1700, 2000, 2300, 2600 and 2900 J, and the stroke values in each test were set at 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 mm, respectively. Two compacts of each specification are produced under the condition of the spring complete releasing. The impact velocity is measured by photoelectric sensor. Then the spring energy storage calculated by the impact velocity is compared with the set energy on touch screen to validate the energy control. The speed measurement results of photoelectric sensor are read by developed Labview software.

4.2. Experimental results
The experimental results of spring energy are compared with the input values and the calculated values, as shown in Figure 4. The measurement results coincide with the set value. The minimum error is 0.7% and the maximum error is 7.2% in the ten sets of tests. The factors causing errors include hydraulic fluctuation, shooting delay, complexity of test environment and limitation of maximum sampling frequency of data acquisition card in the system control. The experimental results indicate that the updating machine has the ability of energy automatic control.

![Figure 4. Comparison between set and experiment results](image)

5. Conclusion
(1) A hydraulic control method for spring energy storage is proposed. The hydraulic and servo system are designed with PLC coding. Then the auto control system is implemented by updating the existing machine.
(2) The PID optimization is employed to reduce the control error and promote the accuracy. The optimal solution of the PID parameters is obtained by the genetic algorithm codes.
(3) In both of the energy control and stroke control experiments of the iron powder compaction, the energy storage of the spring is calculated by measuring impact velocity. The experimental results indicate that the proposed control system has the ability of automatic control of stroke and energy. And the relative density of powder compacts reaches a higher value 98.6%. The energy control method is validated.

6. References
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