Adaptive Control System of Hydraulic Pressure Based on The Mathematical Modeling

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Abstract. In this paper, the authors highlight the problem of replacing an old heavy industrial equipment, and offer the replacement of obsolete control systems on the modern adaptive control system, which takes into account changes in the hydraulic system of the press and compensates them with a corrective action. The proposed system can reduce a water hammer and thereby increase the durability of the hydraulic system and tools.

Introduction

In the modern economic conditions for the industrial enterprises the matter of great importance is the production of the competitive goods with the minimum costs. Production of products and details by the methods of form changing operations is characterized its metal expenditure economy, the ability to get details of high accuracy. Providing optimal parameters for the equipment operation, in particular due to the use of automation systems achieved the rise of its endurance parameters and production energy efficiency.

A great number of technological processes for pressure metal treatment are performed at the hydraulic equipment. Modern hydraulic presses have automated control systems of electric and hydraulic drives, calibrating, beam deskewing, product quality analysis and tooling conditions. However not all the manufacturing enterprises have an opportunity to replace available hydraulic equipment fleet with a new one. Modern information technologies and technical means of automation allow modernizing any equipment with the minimum costs.

To implement automation systems and optimize equipment operating conditions it is necessary to have a vision of dynamic processes occurring in the systems at performing operations and the connections between the operation of the hydraulic system, electric drive and the main operational unit.

In this article the authors introduce hydraulic automation system different by control algorithms of electric and hydraulic drives allowing to diagnose and keep track of system operation during the technological process online and produce correcting control actions. For the prototype sample used hydraulic press with 630 kN force of LF model 2428A where blanking/perforating dies and roller die stamping were installed.
The peculiarity of hydraulic presses as hydraulic driven machine tools is their equipment with high volumes of hydraulic fluid in cylinders and pipelines hence at their operation may occur dynamic processes of fluid pressure fluctuations in hydraulic system. Matters of hydraulic presses dynamics were under consideration of such scientists as B.V. Rozanov, A.I. Zimin, M.V. Storozhev, A. L. Vorontsov[1] who noted that as a consequence of elastic deformation in the systems of hydraulic presses finds hard to complete the operation with sharp load release as observed a fluid hammer, press vibration, seal failure and beam deskewing. Implementation of adaptive control systems capable to register and decrease dynamic oscillation processes into out-dated hydraulic equipment let us to minimize the costs on production reequipment and also achieve quality increase in production and energy efficiency of technological processes.

The questions of adaptive control of the press were raised by S.S. Oding, I.A. Kretov, A. S. Morse [2] who developed algorithm for records of work material parameters deviations included into the mathematical material model allowing to correct the program of deviations immediately at forming. However in their works they dealt with only technological process of draw-forming and comparison was carried out with the parameters written in the simplified mathematical model.

Adaptive control systems for pneumatic drives on the basis of the mathematical modeling were investigated by Michael Brian Thomas[3]. In his writings he justifies the efficiency for implementation of automated adaptive control systems on the basis of mathematical modeling.

1. Concept

Under the made assumptions the processes of slider movement and press frame in technological processes of form changing are described by a set of the first order differential equations including slider movement equations, fluid pressure changes equations in pressure and drain press lines, speeds of slider, change of pressure pump, movement and speed of frame, change of pressure in the head end at different pump mode (1).

Mathematical modeling of equipment hydraulic operation with regard to hydraulic pump operation parameters significantly decreases the number of assumptions such as fluid compressibility, non-uniformity of fluid supply by the pump and fluid flow through the valve[4]. Modeling of pump gives an opportunity to examine pressure in the head end at different pump modes, to estimate the loads on controls due to pressure in the head end and to optimize control system.

\[
F_2(dx_2/dt) - F_2(dx_1/dt) - q_2
\]

(1)

\(M_1 \) – slider mass with attached tools; \(M_2 \) – frame mass; \(x_1, v_1, t_1 \) – movement; speed, and time of slider movement; \(x_2, v_2 \) – movement and speed of frame; \(c_2 \) – coefficient of foundation bolt firmness; \(P_{sn} \) – strain resistance of cutting material; \(F_1, F_2 \) – piston area of working and return cavity; \(Q_h \) – head end geometric delivery; \(p_h \) – pressure in head end; \(R_h \) – head end radius; \(k_1 \) – leakage coefficient; \(p_1, p_2 \) – fluid pressure in the working and return cavity of the cylinder; \(Q_p \) – pump output; \(\alpha_1, \alpha_2 \) – stiffness coefficient of pressure and drain hydraulic press lines; \(q_2 \) – fluid flow rate through the throttle; \(\gamma \) – tilt angle of hydraulic pump; \(x_3 \) – head end movement in hydraulic pump; \(\Theta \) – angle of distributor turn; \(\beta \) – additional angle in plane, perpendicular to the plane formed by kinematic neutral point and its projection on a reference pane; \(d_n \) – piston diameter; \(S_{th}(\Theta) \) – area of window throttling.

As a result of apparent movement at opposing motion of sliding bearing and frame the function \(P_{sn}=f(x_1-x_2)\) exists within \((x_1-x_2)=h_M\), where \(h_M \) – length of stroke.

Functions \(P_{sn}=f(x_1-x_2)\) and \(q_2=f(p_2)\) are highly nonlinear.

The solution of the equation system (1) and research of the parameters influence on dynamic processes are carried out by numerical integration on PC.

Deformation stress of plate sheet metal at equation \(P_{sn}=f(x_1-x_2)\) is taken as an analytical expression taking into account metal variable resistance shear depending on plastic characteristics of cutting metal and cutting punch penetration depth.
Figure 1 illustrates diagrams of deformation resistance at cutting / punching and roll stamping. The part of diagram \( P_{sn} \) at material chips during cutting is described by the following equation:

\[
P_{sn}^{\text{max}} = P_0 + a[(h_M - x_1 - x_2)/(h_K - h_K)]^{(1 - K_2)/K_2}
\]  

where \( P_0 \) – pushing force of punch after cutting, \( P_{sn}^{\text{max}} \) – maximum resistance of deformation of cutting material; 
\( a = P_{sn}^{\text{max}} - P_0 \),
\( K_2 \) – coefficient of diagram loading factor of working loading in segment of chip (find by empirical method), \( 0 < K_2 < 1 \).

![Diagrams](image)

**Figure 1** – Diagrams of deformation resistance (a) at cutting / punching and (b) at roll stamping: 
\( h_M \) – full way of sliding bearing through the material, \( h_K \) – way of sliding bearing from the contact with slug till the beginning of chip

The contraction of area at fracture as a rule is equal to percent reduction of area, hence \( P_{sn} = P_{sn}^{\text{max}} \).

Performed experimental researches allowed getting diagrams of resistance deformation at different technological processes. In a mathematical model (1) deformation resistance \( P_{sn} \) is presented as curve equations such as equation (3) for technological process of roll stamping and it also helps us to improve accuracy of calculations.

\[
(f) = (253.362x - 86.3863x^2 + 14.6373x^3 + 10.9418x^4 - 1.81233x^5 + 0.141945x^6 - 0.00434566x^7)/(2.82589 + 11.1995x - 6.45885x^2 + x^3)
\]  

Mathematical model (1) allows:

- Studying of influence of hydraulic press parameters on dynamic processes at shearing operations;
- Considering hydraulic press as a universal system where movement of its working parts, tool and processed slug that give an opportunity to design processes with optimal parameters and optimal control.

To realize computer modeling was chosen graphical programming environment LabVIEW. The advantage of graphical programming environment use of LabVIEW in modeling includes functions (virtual instruments) allowing to solve differential equations at the time of close to real by Runge-Kutta method of the second order.

The programs executing computer modeling and data visualization were created (Figure 2).
Figure 2 – Picture of computer modeling program window

Computer modeling system of hydraulic press work at technological processes of metal working process allowed to define dependences of equipment work parameters and acknowledge that control system of hydraulic equipment registering calibrated values deviations lets us to define technical malfunctions or equipment deterioration. Study of the results of computer modeling shows parameters demanding control and management.

Developed the structural scheme (figure 3) of automated control system of technological form changing process that is realized on the equipment including connections between the basic system parameters.
The system in real-time mode receives information from RT pressure sensors situated on sliding bearing and frame; information through ATS is being delivered to the computer that is operator desk; production control is implemented with the help of computer vision, i.e. camera transmits a signal that is processed in LabVIEW by intellectual algorithms; electronic computing machine processes information and compares values with the values got by computer modeling of technological process. In case of system detecting deviation of one of the parameters of technological process, it gives the operator recommendations how to optimize the work. If the operator is out of his working place, the switch unit turns on the automation mode where automatic control system controls parameters of technological process with the help of step motors, frequency converters and relay blocks.

The common structure of control system is given in the figure 4. In automatic mode of work PC-controller presets initial values $x(t)=p_0(t), x_0(t), \nu_0(t)$, influencing on engine rotational speed of hydraulic pump $\omega$ and fluid consumption flowing through throttle $q$. Sensors located on hydraulic press deliver calculated parameters to the self-tuning block comparing data received by experimental way and computing method defines correctional coefficient $k_{cor}$, using logical control law: if $|p_{exp}|<0.2*|p_{math}|$, then $k_{cor}=p_{exp}*k_1$; otherwise $k_{cor}=p_{exp}*k_2$; where $k_1<k_2$. Regulator forms control impact $U(t)$ and delivers it to the operating controller.
Control system consists of two microcontrollers[5] and one PC-controller[6]. Algorithm of the basic control system for PC-controller is given in the figure 5. The following consequences of actions are carried out: 1 – Start; 2 – Input experiment name, comment and $N$ – quantity of demanded cycles; 3 – Choice of technological process; 4 – Technological process of cutting/perforating; 5 – Technological process of roll blanking; 6 – Turn on frequency converter hydraulic pump and transfer beam in the maximum position; 7 – Login procedure of data acquisition device; 8 – Diagnostic routine of microcontroller modules including into control system; 9 – Mode selection: Automatic control; 10 – Demand assignment at microcontroller 1; 11 – Switch to microcontroller 1; 12 – Switch the basic system into sleep mode; 13 – Insert data about material: $L$, $d$, $h$; 14 – Selection of material and its parameters; 15 – 19 – Material type, density, strain resistance diagram and so on; 20 – Selection of working conditions for equipment; 21-25 – Parameters of regulation, pressure, speed and so on; 26 - Data acquisition from ATS; 27 – Data cleaning; 28 – Data processing and conversion into $C$; 29 – Solution of differential equations by second order Runge-Kutta method; 30 – Screen display of diagrams and data; 31 – Program of data comparison; 32 – $i=N$?; 33 – Do you want to change $N$ cycles and continue working; 34 – Do you finish your work or choose other parameters? 35 – End of program.
Figure 5 – Algorithm of Automated Control System

Working principle of PID controller, i.e. the difference between current pressure and pressure received due to the results of computer modeling is multiplied by configurable factor and we get capacity which is necessary to show at the present moment in output control device. Proportional term works at the moment of occurring mismatching. When cross beam starts moving, capacity begins decreasing, and when it achieves minimum mark, device is turned off. The effect from the impact is shown with a delay and environment also affects the object, so, cross beam mass, fluid and pipe line compressibility. To compensate “external” influences integral term was added in the circuit. As a result of such an approach integral becomes stable that is why value of output capacity turns out permanent. Moreover, as there is a required pressure then mismatching is absent, proportional term doesn’t work at all. To compensate impact of delays between the influence and reaction of the system in the system was added a differential term.

Simply proportional regulator gives capacity all the time until pressure reaches required point; proportional-differential one starts decreasing supplied capacity before cross beam attains required point. As mismatching is reducing, there is a negative derivative decreasing the influence. That allows minimizing the pressure at higher scale transitions.

We made a plan of the experiment including 13 tests in each of six experiments; sample size was calculated and justified. And hereby as a variable parameter was chosen a controlled parameter of sectional area for throttle shelter \( q \). Analyzed parameters were admitted the following parameters – pressure at pressure main \( p_h \), cross beam speed \( v_b \), cross beam movement \( x_b \), frame movement \( x_f \).

Correlation dependences of cross beam movement speed from throttle shelter at roll stamping procedure, shown in the figure 6 (a) and pressure dependences in the pressure main from throttle shelter area in the figure 6 (b), allows acknowledging adequacy of the developed mathematical model. Errors are situated within permitted values; hence, computer model designed on the basis of the mathematical one works correctly and can be used at the development of control systems of hydraulic equipment.
Conclusion

Basing on the results of the theoretical and experimental researches got task solution at the development of automated control system for hydraulic equipment on the basis of adaptive algorithms built on mathematical models, being important to industrial enterprises or research societies.

Developed mathematical model allows us researching the influence of hydraulic unit parameters on dynamical processes at shearing operations; moreover, hydraulic press is considered as a single system where there is a movement of its working objects, tools and processed work piece that gives an opportunity to design machines with optimal parameters and with optimal control, and to serve as a basis for calculations of processes in presses at operations with long working cycle. Researches passed approbation in real production enterprise that is affirmed by adoption deed. Automated control of hydraulic working parameters lets to optimize energy costs for technological process, to reduce consumption and to increase working tool wear resistance.

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Figure 6 – Diagrams of dependences at roll stamping procedures – speed of cross beam movement, b) pressures in the pressure main from throttle shelter area