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Mechatronic Hydraulic Drive with Regulator, Based on Artificial Neural Network

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Abstract. Mechatronic hydraulic drives, based on variable pump, proportional hydraulics and controllers find wide application in technological machines and testing equipment. Mechatronic hydraulic drives provide necessary parameters of actuating elements motion with the possibility of their correction in case of external loads change. This enables to improve the quality of working operations, increase the capacity of machines. The scheme of mechatronic hydraulic drive, based on the pump, hydraulic cylinder, proportional valve with electrohydraulic control and programmable controller is suggested. Algorithm for the control of mechatronic hydraulic drive to provide necessary pressure change law in hydraulic cylinder is developed. For the realization of control algorithm in the controller artificial neural networks are used. Mathematical model of mechatronic hydraulic drive, enabling to create the training base for adjustment of artificial neural networks of the regulator is developed.

1. Introduction

The study of operating processes of metal processing allows to determine the optimum processing modes [1-3]. It improves the quality of detail processing, reduces the number of defects. The capabilities of the technological equipment for metal treatment under pressure relating to the ensuring of optimum modes significantly extend in case of the use of mechatronic hydraulic drives with proportional program control [4-7]. Currently, the development and introduction of mechatronic hydraulic drives in technological machines for metal treatment under pressure corresponds to the global trends of design of such machines, and the development of structure and determination of effective algorithms of mechatronic hydraulic drive control is a recent scientific and technical problem [4].

The objective of this paper is to develop a scheme of a mechatronic hydraulic drive with regulator that provides the possibility of implementation of the necessary load laws of a workpiece in the process of their deformation.

2. The scheme of a mechatronic hydraulic drive

The scheme of a mechatronic hydraulic drive is presented in figure 1. The hydraulic drive includes an adjustable pump 1, a distributor 2, a hydraulic cylinder 3 and a controller 4. The adjustable pump is equipped with a regulator 19 that includes a spool valve 8 with a spring 9, throttles 14, 16 and a valve 7 with an electromagnet 6. A faceplate 13 of an adjustable pump 1 is controlled by servo-cylinders 11 and 12. The hydraulic fluid is delivered to servo-cylinder 11 from a regulator 19 through the damper 15. The controller 4 through the amplifier 17 and 18 is connected to the distributor 2 and 5 through the amplifier 5 to the regulator 19. The signals given by the controller 4 modes determine the hydraulic



drive operating regime and load changes laws of workpieces in the process of processing. The regulator 19 is connected through the hydraulic line 20 with the distributor 2. The hydraulic line 10 is connected to the controller 4 through the pressure sensor 21.

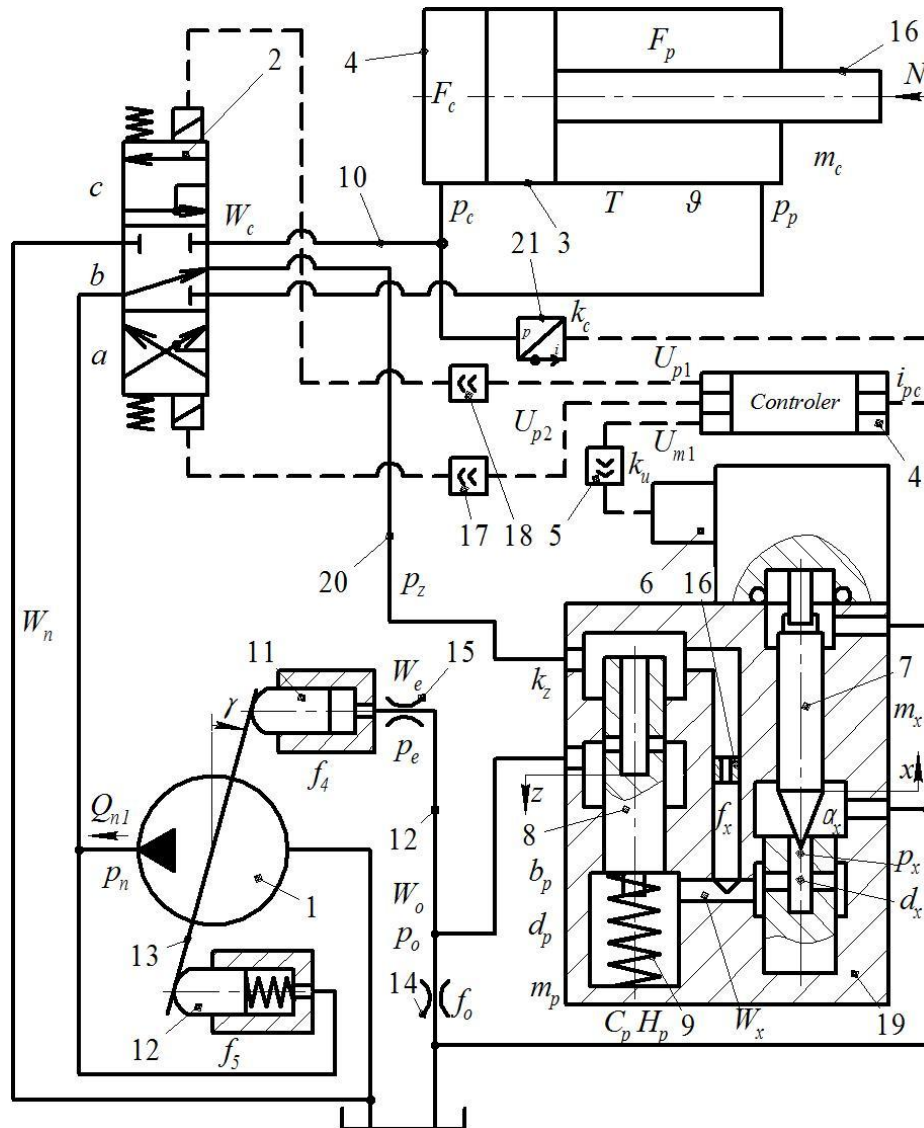


Figure 1. The scheme of a mechatronic hydraulic drive.

The hydraulic drive operates in such a way. When finding a distributor in a position (b) the adjustable pump 1 is disconnected from the hydraulic cylinder, but delivers a hydraulic fluid through the hydraulic line 20 to the regulator 19. The controller 4 thus delivers a zero signal to the electromagnet 6. The hydraulic fluid from the hydraulic line 20 will enter through the throttle 16 and valve work window to the drain, and simultaneously through the spool valve work window 8 and damper 15 to servo-cylinder 11. A faceplate 13 of an adjustable pump 1, which is currently under servo-cylinders 11 and 12 operation will unfold downward the angle γ reduction and the pump output flow will be minor. Delivery pressure of the adjustable pump 1 will be determined by adjusting the spring 9 and will be 1.0 MPa, and the pump output flow in this mode compensates only a small flow of hydraulic fluid that occurs in the regulator 19. Thus when finding a distributor 2 in a positions (b) pump discharge mode is provided, in which capacity loss in the hydraulic drive is minor.

When switching the distributor into position (a) hydraulic fluid from the adjustable pump 1 through the distributor 2 will flow into a hydraulic cylinder 3 head end. The hydraulic cylinder 3 rod will move from left to right until it stops at the work piece to be deformed. Drain of the hydraulic fluid from the hydraulic cylinder rod end is also through distributor 2. Therewith the controller 4 generates a signal U_{m1} , which through the amplifier 5 is delivered to the electromagnet 6. The electromagnet 6 influences the valve 7 and creates pressure p_x in the spring chamber of the spool valve 9. Therewith the value of pressure p_x is proportional to the signal U_{m1} . Pressure p_x influences the spool valve 8 and with the spring 9 forms pressure p_x above the upper end of the spool valve. Pressure p_x will determine the magnitude of pressure p_z , which occurs in the hydraulic cylinder head end. Thus, the value of pressure p_z , which determines the force N on hydraulic cylinder 3 rod 16 will be proportional to the signal U_{m1} value at the output of the controller 4.

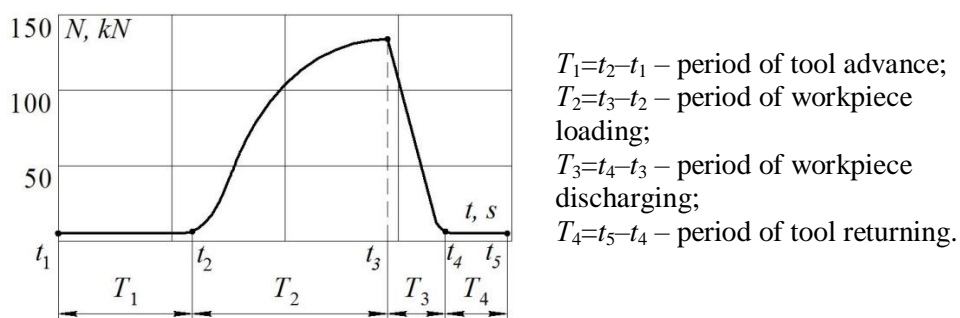


Figure 2. The workpiece load law

Setting the law of variation of signal U_{m1} over time may provide the necessary law of variation of pressure p_z in the hydraulic cylinder 3 head end and accordingly the law of variation of the value of force N on the rod [4]. Figure 2 shows the dependence of the force N on the hydraulic cylinder 3 rod from the time during operation of the mechatronic hydraulic drive in the mode when the distributor 2 is in position (a). This mode is called load conditions and has three specific periods. During $T_1 = t_2 - t_1$ the controller 4 generates a signal $U_{m1} = 0$ and in this period hydraulic cylinder rod 16 with the tool fixed on it is fed to the work piece. Force p_z in the hydraulic cylinder 3 head end is thus determined by adjusting the spring 9 of the regulator 19. In time t_2 period by a signal from the pressure sensor controller 21 starts changing signal U_{m1} , by law, which is determined by the control algorithm and is optimal for this type of processing and type of workpiece [4]. Workpiece loading takes place during the period $T_2 = t_3 - t_2$. At time t_3 the law of variation of signal U_{m1} changes and force N changes accordingly, influencing the workpiece. Unloading of the workpiece takes place during $T_3 = t_4 - t_3$. At time t_4 distributor 2 switches into position (c). The hydraulic fluid from the adjustable pump 1 through the distributor 2 will be delivered to the hydraulic cylinder 3 head end and the rod will move from right to left deflecting the tool from the workpiece. In the period $T_4 = t_5 - t_4$ the signal U_{m1} at the output of the controller is zero, and the pressure p_{pz} in the head end will be determined by adjusting the regulator 19 spring 9. In the period $t_5 - t_4$ mode, called "tool returning" will be implemented.

Formation of required law during processing is provided by the controller. The controller functions as a regulator, a block diagram of which is shown in figure 3. The regulator includes shift units 2 and 5, and artificial neural networks 3 and 4. The signal p_c from the pressure sensor transfers to the input regulator. Depending on the operating regime of mechatronic, hydraulic drive regulator generates the following signals: U_{p1} , U_{p2} – voltage fed to the electromagnets of the distributor; U_{m1} – voltage fed to the electromagnet of the pump regulator.

Shift units 2 and 5 maintain operation of the regulator at such mechatronic hydraulic drive operating modes:

1. Pump discharge mode $U_{p1} = U_{p2} = 0$; $U_{m1} = 0$
2. Valve hydraulic-cylinder rod travel with the tool

- 2.1. Accelerated tool advance $U_{p1}=0; U_{p2}=\max; U_{m1}=0$
 2.2. Workpiece loading $U_{p1}=0; U_{p2}=\max; U_{m1}=F_1(t)$
 2.3. Workpiece discharging $U_{p1}=0; U_{p2}=\max; U_{m1}=F_2(t)$
 3. Tool returning $U_{p1}=\max; U_{p2}=0; U_{m1}=0$
 $F_1(t), F_2(t)$ are indicated – transfer functions of neural networks 3 and 4.

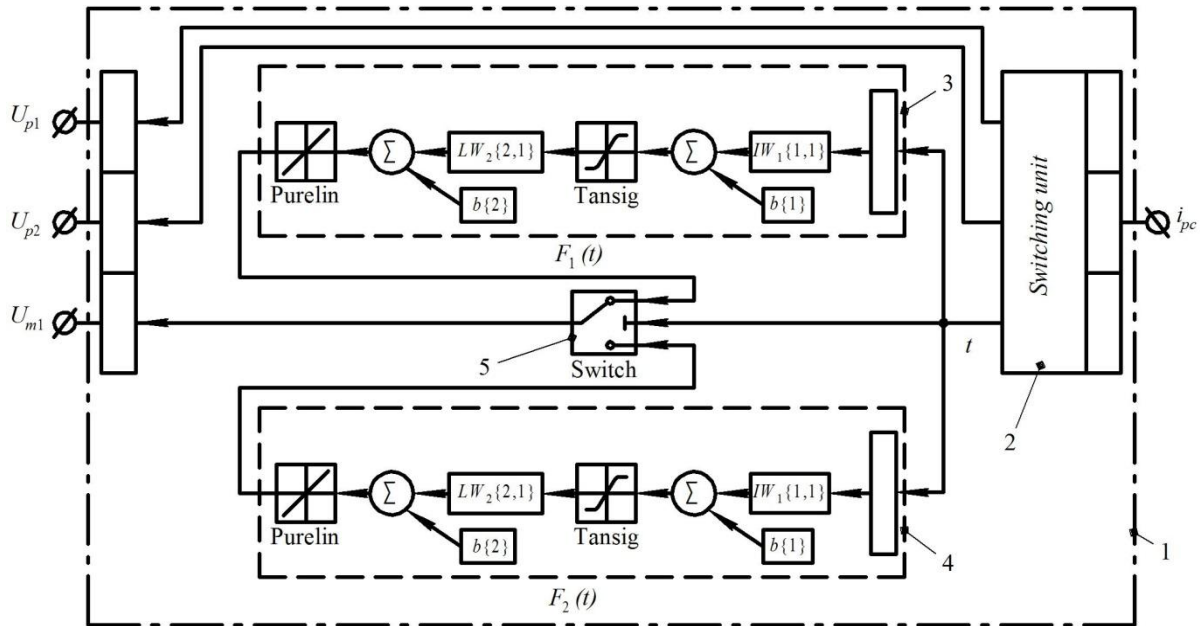


Figure 3. The block diagram of the controller, based on artificial neural network.

Necessary laws of load changes on the workpiece that are determined by the nature of pressure p_z change during the processing are formed by neural networks. Load law on the workpiece during the period $T_2=t_3-t_2$ is determined by the neural network 4, during the period $T_4=t_5-t_4$ by the neural network 4.

Checking of operability and efficiency of mechatronic hydraulic drive at the design stage may be performed on the basis of simulative mathematical modeling.

3. Mathematical model and simulation results of mechatronic hydraulic drive

Mathematical model of mechatronic hydraulic drive comprises of moment (1) equation acting on the pump faceplate 13 (figure 1), force (2) equation acting on the valve 7, force (3) equation acting on the spool 8, force (4) equation acting on the 3 hydraulic-cylinder rod 16 and flow continuity (5) equation for hydraulic lines between the regulated pump 1, hydraulic cylinder 3 and regulator 19, flow continuity (6) equation for hydraulic lines between the spool 8, a damper 15 and the throttle valve 4, flow continuity (7) equation for hydraulic line between the throttle valve 16 and the valve working window 7, flow continuity (8) equation for hydraulic lines between the damper 15 and servo-cylinder 11, voltage drop (9) equation in the circuit of the electromagnet 6, the dependence (10) of compliance factor b_n , which describes the total compression of the hydraulic fluid and rubber-steel pipelines, dependence (11), which determines the adjusted modulus the hydraulic fluid given the presence of the gas phase. Structure blocks that implement transfer functions $F_1(t), F_2(t)$ of neural networks are also included into mathematical model.

The mathematical model of the mechatronic hydraulic drive is designed at such basic assumptions and simplifications. The focused hydraulic drive parameters are considered; the temperature during working hours does not change; wave processes in hydraulic lines were not considered; flow coefficients through the throttle, working windows of a spool 8 valve 7 are constant; pressure loss in

hydraulic lines and in working windows of the distributor 2 were not inspected; hydraulic drive operation mode is non-cavitating; dry friction force in hydraulic cylinder does not depend on the rod travel speed; operation of an electromagnet amplifier of the pump control valve is measured with the help of the proportional link.

$$I \frac{d^2 \gamma}{dt^2} = p_c \cdot f_5 \cdot l - p_e \cdot f_4 \cdot l - \frac{\pi \cdot \rho \cdot v_k \cdot d_4 \cdot l_4}{\varepsilon_n} \cdot \frac{d\gamma}{dt} \cdot \cos \gamma + m_0 + m_1 \cdot Q_{n1} + m_2 \cdot p_{n1} + m_3 \cdot Q_{n1}^2 + m_4 \cdot p_{n1}^2 + m_5 \cdot p_{n1} \cdot Q_{n1} + m_f(\omega_n) \quad (1)$$

$$m_x \frac{d^2 x}{dt^2} = p_x \cdot \frac{\pi \cdot d_x^2}{4} - k_m \cdot i_{m1} - \left(\frac{\pi \cdot \rho \cdot v_k \cdot d_x \cdot l_x}{\varepsilon_x} \right) \cdot \frac{dx}{dt} \quad (2)$$

$$m_p \frac{d^2 z}{dt^2} = p_c \frac{\pi \cdot d_p^2}{4} - p_x \frac{\pi \cdot d_p^2}{4} - C_p \cdot (H_p + z) - \frac{\pi \cdot \rho \cdot v_k \cdot d_p \cdot l_p}{\varepsilon_p} \cdot \frac{dz}{dt} \quad (3)$$

$$m_c \frac{dv}{dt} = p_c \cdot F_c - \pi \cdot D_{cz} \cdot (q_0 + k_q \cdot p_c) - N \quad (4)$$

$$F_7 \cdot d_8 \cdot k_1 \cdot n_n \cdot \operatorname{tg} \gamma - k_n \cdot p_{n1} = \mu \cdot k_z \cdot z \cdot \sqrt{\frac{2 \cdot |p_{n1} - p_0|}{\rho}} \cdot \operatorname{sign}(p_{n1} - p_0) + \beta_n \cdot W_c \frac{dp_c}{dt} \quad (5)$$

$$\mu \cdot k_z \cdot z \cdot \sqrt{\frac{2 \cdot |p_c - p_0|}{\rho}} \cdot \operatorname{sign}(p_c - p_0) = \mu \cdot f_0 \cdot \sqrt{\frac{2 \cdot p_0}{\rho}} + \beta_p \cdot W_0 \frac{dp_0}{dt} + \mu \cdot f_e \cdot \sqrt{\frac{2 \cdot |p_0 - p_e|}{\rho}} \cdot \operatorname{sign}(p_0 - p_e) \quad (6)$$

$$\mu \cdot f_x \cdot \sqrt{\frac{2 \cdot |p_c - p_x|}{\rho}} \cdot \operatorname{sign}(p_c - p_x) = \mu \cdot \pi \cdot d_x \cdot x \cdot \sin\left(\frac{\alpha_x}{2}\right) \cdot \sqrt{\frac{2 \cdot p_x}{\rho}} + \beta_p \cdot W_x \frac{dp_x}{dt} \quad (7)$$

$$\mu \cdot f_e \cdot \sqrt{\frac{2 \cdot |p_0 - p_e|}{\rho}} \cdot \operatorname{sign}(p_0 - p_e) = \beta_p \cdot W_e \frac{dp_e}{dt} - \exp(A_b \cdot p_e + B_b \cdot t^\circ + C_b \cdot \varepsilon_e + D_b) - f_4 \cdot l \cdot \frac{d\gamma}{dt} \cdot \cos \gamma \quad (8)$$

$$L_e \frac{di_{m1}}{dt} + i_{m1} \cdot R_e = \begin{cases} 0 & \text{by } t_1 \leq t < t_2 \\ k_u \cdot F_1(t) & \text{by } t_2 \leq t < t_3 \\ k_u \cdot F_2(t) & \text{by } t_3 \leq t < t_4 \\ 0 & \text{by } t_4 \leq t < t_5 \end{cases} \quad (9)$$

$$\beta_n = \frac{1}{E_p} + \frac{d_{mp}}{\delta_{mp} \cdot E_{mp}(p)} \quad (10)$$

$$E_p = \frac{1}{\beta_p} = E_{p0} \frac{W_f / W_a + 1}{W_f / W_a + (E_{p0} \cdot p_0) / p^2} \quad (11)$$

where p_c, p_p, p_e, p_z, p_0 – pressure at the in-outlet of the hydraulic cylinder 3 (figure 1), in the pump control system 1; z – coordinate position of the spool regulator 8; γ – rotation angle of the adjustable pump faceplate 1; f_0 – throttle area 14 in the pump control system; F_c, F_p, f_4, f_5, f_e – piston surface area of the hydraulic cylinder 3, of servo-cylinders of the regulated pump, of the damper of pump servo-cylinder; D_c, d_p, d_7, d_8, d_x – diameters of hydraulic cylinder 3, of slide valve 8 of regulator, feeds plungers of the adjustable pump and the contact circle of the pump feeds with the faceplate, working window of the valve 7; k_q, k_m, k_n, k_c, k_u – coefficients specific friction force in the hydraulic cylinder 3, efforts proportionality of the electromagnet, of pump leaks 1, pressure transducer reinforcement 21 and reinforcers 5; L_e, R_e – coefficient of induction and active resistance of the winding 6; i_{m1}, i_{pc} – currents in the winding of the valve 17, in the outlet of the pressure transducer 21; N, T – load force on the throttle 16 and friction in the hydraulic cylinder 3; μ – flow coefficient through the throttle and

spool elements; ρ – hydraulic fluid density; l_p, l_4, l – spool contact length 8, pump servo-cylinder 11, arm of action of the servo-cylinders of the regulated pump 1; I – moment of the inertia of the faceplate 13 of the pump; m_p – spool mass 8; W_0, W_c – hydraulic lines between the regulator 8, throttle 14 and damper 15, between the pump 1 and hydraulic cylinder 3; n_n – rate speed of the pump shelf assembly 1; k_1 – quantity of the feed plunger 1; q_0 – specific friction force in hydraulic cylinder 3; $\varepsilon_p, \varepsilon_n$ – gaps between the spool 8, servo-cylinder of the pump 11 and their corpuses; $F_1(t), F_2(t)$ – transfer functions, which are implemented by neural networks; m_0, m_1, m_2, m_3 – coefficients of dependency of the resistance moment on the faceplate 13 of the pump of flow and pressure; A_b, B_b, C_b, D_b – coefficient in flow formula from servo-cylinder control camera 11; β_p – reduced compliance coefficient of the gas-liquid mixture; β_n – reduces compliance coefficient of the rubber-metal pipeworks and gas-liquid mixture; $E_{p0}, E_p, E_{pm}(p)$ – elasticity modulus of the working liquid, reduced elasticity modulus of the gas-liquid mixture and rubber-metal pipeworks; δ_{mp} – thickness of the pipework wall; W_f – liquid volume in the gas-liquid mixture at pressure p ; W_a – gas volume in the gas-liquid mixture at atmosphere pressure.

Neural networks used in a regulator of mechatronic hydraulic drive are generated with the help of the application Neural Network Toolbox that is a part of the software package MATLAB [8]. Classical neural networks with a direct signal propagation are used. These neural networks perform the function:

$$net=newff(PR[S1, S2..SN1] TF1, TF2..TFN1, BTF, BLF, PF) \quad (12)$$

where PR – signal values in the input and output of the neural network, taken form the database, $S1, S2..SN1$ – quantity of neurons in the hidden layers of the neural networks; $TF1, TF2..TFN1$ – activation functions for the hidden layers; BTF – learning neural networks function; BLF – weight coefficients and bias adjustment feature; PF – inaccuracy function.

Function parameters *newff*: activation function for the hidden layer neurons – *tansig*, for the output neuron – *purelin*, neural network learning function by the classical scheme of the back propagation of error – *traingd*, function of the weight coefficients and bias settings – *learnqdm*, inaccuracy function – *mse* are used in the process of neural network generation and learning.

During the training process for the termination process, the following parameters are controlled: *epochs* – the maximum number of learning cycles, *goal* – functional training threshold value, *max-fail* – the maximum permissible level of error exceeding of the reference sample in comparison with the training.

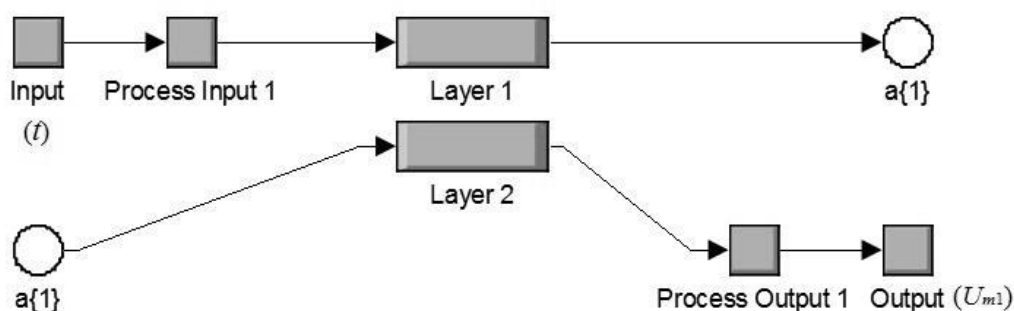


Figure 4. Structure of neural network that tools the workpiece load law.

Neural network, providing workpiece load has 6 hidden layer neurons. The structure of the neural network is formed in MATLAB-Simulink environment and is presented in figure 4. Figure 5 shows the structure of the hidden layer neurons of the neural network.

For the neural network instruction training bases built on the results of work are used [4]. Neural network training base that provides work piece loading consisted of 27 pairs of data, and the neural network base that provides work piece unloading consisted of 22 pairs of data.

In the course of the neural network training, providing work piece loading 25 iterations were held. Weight coefficients and neural network bias were determined.

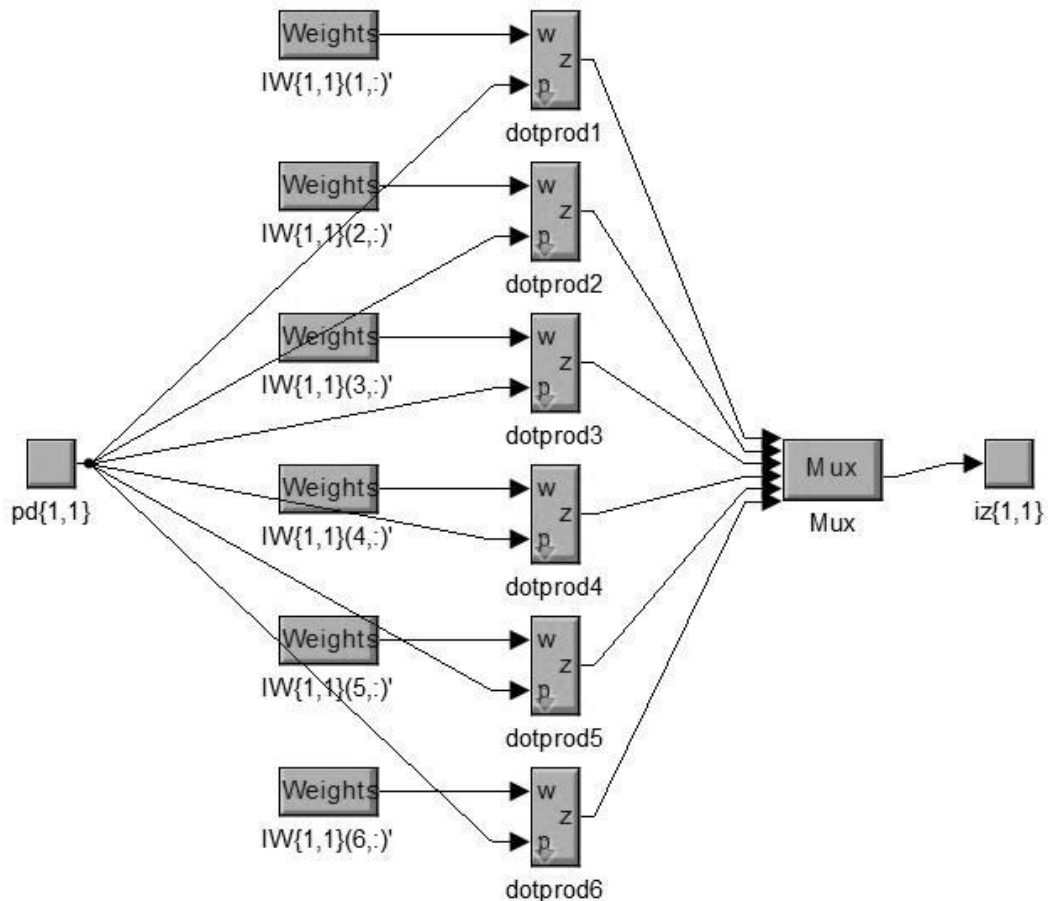


Figure 5. Structure of neurons hidden layer in a neural network that tools the workpiece load law.

Weight coefficients vector of neurons hidden layer of this neural network: $iw_1\{1,1\} = (-8,619; 8,010; -8,415; -11,631; 5,880; -5,190)$.

Neurons hidden layer displacement vector: $b\{1\} = (8.107, -3.439, 0.321, -2.158, 2.676, -7.290)$. Inputs vector for the neuron output layer: $LW_2\{2,1\} = (0,009; 0,033; -0,127; -0,125; 0,677; -2,062)$. Output neuron displacement: $b\{2\} = (-2.052)$.

The maximum deviation value result of the neural network of the corresponding value of the training base is 2.2%.

Neural network that provides unloading of the workpiece has 7 neurons in the hidden layer. In the course of training of this neural network 12 iterations are held.

Weight coefficients and neural network bias were determined. Weight coefficients vector of the neural network is the following: $iw_1\{1,1\} = (-9,642; -9,793; 9,678; 9,777; -9,737; 9,69; -9,803)$.

Vector displacement of neurons hidden layer: $b\{1\} = (9.931, 6.497, -3.468, 0.086, -3.173, 6.558, -9.571)$.

Vector displacement of the neuron output layer: $LW_2\{2,1\} = (0,025; 0,022; -0,163; -0,186; 0,278; -0,233; 0,165)$.

Output neuron bias: $b\{2\} = (0,035)$.

The maximum deviation value result of the neural network of the corresponding value of the training base of 2.4%.

4. Conclusion

Represented scheme of the mechatronic hydraulic drive with regulator based on artificial neural networks enables loading and unloading of workpieces with necessary laws during processing. The use of neural networks enables implementation of complex nonlinear load laws and minimize labor costs to prepare regulatory control algorithms owing to existing developed mathematical apparatus of artificial neural networks and distributed software. Designed mathematical model of mechatronic hydraulic drive is the basis for determining its operability and performance in the design phase.

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