Simulation of the testing process of reciprocating hydraulic cylinders with energy recovery

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Abstract. One of the most important problems of modern mechanical engineering is the energy efficiency of technological equipment and manufactured products. A separate issue in this series is the technology and means of testing finished product samples, including hydraulic cylinders, which can be carried out with passive or active energy recovery. The purpose of the work is to develop a test bench for piston hydraulic cylinders that provides recovery of part of the energy during the test, and at the same time the tests would take place in a mode as close as possible to the real conditions of their operation during their tests, as well as solving the problem of its modeling and calculation of the main functional parameters.

In this article, a design scheme of a test bench for reciprocating hydraulic cylinders with active energy recovery and a method for mathematical modeling of the process of its functioning based on the application of the “theory of volumetric rigidity of hydraulic systems” is proposed, which makes it possible to describe with a high degree of accuracy and reliability the processes occurring in the test system during its operation. A scheme of a test bench for piston hydraulic cylinders with energy recovery is proposed. A mathematical model of the stand has been developed and an example of a preliminary calculation of its functioning is given. The proposed modeling method simplifies the modeling process and allows the use of numerical integration methods in calculations. The resulting mathematical model makes it possible to obtain rational parameters of the stand already at the design stage, without resorting to the need for expensive and labor-intensive field studies.

1 Introduction

At the current level of industrial production development, energy consumption is growing rapidly, both in the production process and at the stage of operation of technological equipment. One of the most expensive technological processes in the chain of development, research, design, production and operation of technological equipment, including the production of hydraulic drive systems and their elements, is the process of testing the finished...
2 Test bench for reciprocating hydraulic cylinders with energy recovery
The energy supplied to the shaft of the hydraulic pump is converted into hydraulic energy and directed to the first hydraulic cylinder, which in this case performs the functions of a hydraulic motor, is converted into mechanical energy and, by means of mechanical transmission, is transmitted to the rod of the second hydraulic cylinder, which performs the functions of a hydraulic pump, in which it is again converted into hydraulic energy and directed to the input of the hydraulic motor, where it is again converted into mechanical energy of rotation of the shaft of the hydraulic motor and by means of a mechanical transmission (in this case belt) is again supplied to the shaft of the hydraulic pump, where it is combined with the energy supplied from the primary source and converted back into hydraulic energy.

Thus, the energy of testing hydraulic cylinders is not spent on creating "harmful heat", but circulates inside the test system, the electric motor 1 only compensates for the energy losses inside the test system caused by the need to overcome hydraulic and mechanical friction with this system.

3 Simulation of the testing process of piston hydraulic cylinders with energy recovery

It is well known that mathematical modeling of a technical system followed by its theoretical studies aimed at identifying the most important elements of the system that have the greatest impact on quality indicators is the most effective way of preliminary analysis when creating new and original technical solutions [9-11].

3.1 Simulation of the hydraulic system of the test bench

...
\[ dp = C_{prl}(\Sigma Q_{vhi} - \Sigma Q_{ish})dt, \]

\[ dp_1 = C_1(Q_H - Q_{1-2} - Q_{1-3})dt, \]
\[ dp_2 = C_2(Q_{1-2} - Q_{KP6})dt, \]
\[ dp_3 = C_3(Q_{1-3} - Q_{1-4})dt, \]
\[ dp_4 = C_4(Q_{3-4} - Q_{4-5})dt, \]
\[ dp_5 = C_5(Q_{4-5} - Q_{5-6})dt, \]
\[ dp_6 = C_{c9.sht}(Q_{5-6} - v_{p9f_p.sht})dt, \]
\[ dp_7 = C_{c9.p}(v_{p9f_p} - Q_{7-8})dt, \]
\[ dp_8 = C_9(Q_{7-8} - Q_{8-9})dt, \]
\[ dp_9 = C_9(Q_{8-9} - Q_{9-10})dt, \]
\[ dp_{10} = C_{10}(Q_{9-10} - Q_{10-11})dt, \]
\[ dp_{11} = C_{11}(Q_{10-11} - Q_{11-12} - Q_{11-24})dt, \]
\[ dp_{12} = C_{12}(Q_{11-12} - Q_{12-13})dt, \]
\[ dp_{13} = C_{13}(Q_{12-13} - Q_{13-14})dt, \]
\[ dp_{14} = C_{14}(Q_{13-14} - Q_{14-15})dt, \]
\[ dp_{15} = C_{c12.p}(Q_{14-15} - v_{p12f_p})dt, \]
\[ dp_{16} = C_{c12.sht}(v_{p12f_p.sht} - Q_{16-17})dt, \]
\[ dp_{17} = C_{17}(Q_{16-17} - Q_{17-18})dt, \]
\[ dp_{18} = C_{18}(Q_{17-18} - Q_{18-19})dt, \]
\[ dp_{19} = C_{19}(Q_{18-19} - Q_{19-20} - Q_M)dt, \]
\[ dp_{20} = C_{20}(Q_{19-20} + Q_{0K} - Q_{20-21})dt, \]
\[ dp_{21} = C_{21}(Q_{20-21} - Q_{KP15})dt, \]
\[ dp_{22} = C_{22}(Q_{KP15} - Q_{22-23})dt, \]
\[ dp_{23} = C_{23}(Q_{22-23} - Q_{23-24} - Q_{0K})dt, \]
\[ dp_{24} = C_{24}(Q_{23-24} + Q_{M} - Q_{11-24} - Q_{24-0})dt, \]
The flow rates of the working fluid for use in the pressure increment equations are determined by the flow formula:

$$Q_i = \mu f \sqrt{\frac{2}{\rho}} |p_i - p_{i+1}| \cdot \text{sign}(p_i - p_{i+1})$$

where:

- $p_i$ – instantaneous value of the inlet pressure of the corresponding system resistance;
- $p_{i+1}$ – instantaneous pressure value at the outlet of the corresponding system resistance;
- $f$ – the area of the passage section of the corresponding resistance;
- $\mu$ – the flow rate of the corresponding hydraulic resistance;
- $\rho$ – the current value of the working fluid density.

When calculating linear hydraulic resistances, the reduced flow rate of the corresponding hydraulic line is used, determined taking into account the flow regime of the fluid at the time under consideration by the formula:

$$\mu = \mu_l = \frac{1}{\sqrt{\lambda_l l}}$$

where:

- $d_l$ – diameter of the live section of the corresponding hydraulic line;
- $l_l$ – the length of the considered section of the hydraulic line;
- $\lambda_l$ – the coefficient of hydraulic friction of the working fluid on the considered section of the hydraulic line, which is calculated taking into account the flow mode of the fluid.

The given coefficients of volumetric rigidity of metal pipelines are determined by analytical dependencies [12...14]

$$C_l = \frac{4}{\pi d^2 l} \cdot \frac{E_{fl}}{1 + \frac{d E_{fl}}{\delta E_{fl}}}$$

where:

- $d$ – inner diameter of the pipeline section;
- $l$ – the length of the pipeline section under consideration;
- $\delta$ – wall thickness of the pipeline section under consideration;
- $E_{fl}$ – the current value of the elastic modulus of the working fluid;
- $E_{fl}$ – the value of the elastic modulus of the wall material of the pipeline section under consideration.

The given coefficients of volumetric rigidity of the RVD (high-pressure hoses) are determined experimentally [15., 16].

The theoretical supply of the hydraulic pump is determined by the formula:

$$Q_{teor} = q_H n_H$$

where:

- $q_H$ – hydraulic pump working volume;
- $n_H$ – speed of rotation of the hydraulic pump shaft.

The actual instantaneous value of the hydraulic pump performance is determined taking into account the current value of its volumetric efficiency according to the dependencies:
\[ Q_H = Q_{teor} \eta_0, \]
\[ \eta_0 = 1 - (1 - \eta_{o, nom}) \cdot \frac{p_H}{p_{H, nom}}, \]
\[ \eta_{o, nom} = \frac{1 - \eta_0}{1 - \eta_{o, nom}}. \]

3.2 Simulation of the movement of mechanical elements of the hydraulic system of the stand

\[ \frac{dv_{ok}}{dt} = \frac{1}{m_{ok}} \left[ \frac{\pi d_{ok}^2}{4} (p_{23} - p_{20}) - F_{upOК} \right], \]
\[ \frac{dh_{ok}}{dt} = dv_{ok}, \]
\[ \frac{d\omega_M}{dt} = \frac{1}{J_M} [W_M (p_{19} - p_{24}) - M_M], \]
\[ \frac{d\omega_H}{dt} = \frac{1}{J_H} (M_{EM} i_{2,4} + M_M i_{17,4} - \omega_H (p_1 - p_{at})). \]
\[ \omega_M = \omega_H \cdot i_{17,4}. \]
The evaluation of the effectiveness of the testing process was carried out on the basis of calculating the efficiency coefficient of the testing process, which can be used in two types - the instantaneous efficiency coefficient and the average efficiency coefficient, which are determined by the formulas:

\[ k_{efi} = \frac{N_{isp}}{N_{ist}} \]

where 

- \( k_{efi} \) – instantaneous value of the efficiency coefficient of the test process;

- \( N_{isp} \) – power on the tested hydraulic cylinder at the i moment of time;

- \( N_{ist} \) – the power supplied to the input of the primary energy source at the time under consideration;

\[ k_{ef, sr} = \frac{W_{isp}}{W_{ist}} \]

where 

- \( k_{ef, sr} \) – the average value of the efficiency coefficient of the test process;

- \( W_{isp} \) – the energy that has passed through the tested hydraulic machine from the moment of the beginning of the tests to the time under consideration;

- \( W_{ist} \) – the energy consumed by the primary energy source from the start of the tests to the time under consideration.

4 Calculation of the main functional characteristics of the stand

To study the obtained mathematical model, a special program was compiled using the SimInTech differential equation solution unit [17–22].

As a result of preliminary calculations, the functional characteristics of the stand operation were obtained, showing the relationship of the system parameters and the influence of the design parameters of the stand on them.

Figure 2 shows the results of calculating the functional parameters of the test system during its operation.

**Fig. 2.** The results of preliminary calculations of testing piston hydraulic cylinders: a) pressure: 1 at the outlet of the hydraulic pump 5, 2 – in the piston cavity of the hydraulic cylinder 9, 3 – in the stem cavity of the hydraulic cylinder 9, 4 – at the inlet of the hydraulic motor 14; b) the test efficiency coefficient 1 – instantaneous, 2 – average per cycle.

5 Conclusion

Thus, the proposed mathematical model makes it possible to conduct a numerical experiment to study the functioning of the proposed stand. The numerical experiment makes it possible to identify the influence of the main design and functional parameters of the test system on the qualitative characteristics of the test process and, ultimately, to obtain rational parameters of the stand, without resorting to the need for expensive and labor-intensive field studies.
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