Mathematical modelling of the hydromechanical drive of the test bench for plunger hydraulic cylinders with energy recovery

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Abstract. Reliability is a significant parameter of machines, mechanisms, drives, technological equipment and its component parts, including hydraulic motors. Reliability is checked and confirmed by carrying out resource tests, the results of which reveal the characteristics and properties of materials, components and working fluids that are used in the production of hydraulic cylinders and during operation. One of the practical ways to determine reliability is testing. The aim of the work is to improve the theory and methods of calculation and design of the hydromechanical drive system of the service life test bench of plunger hydraulic cylinders through the use of an energy recovery scheme that provides an increase in the energy efficiency of the testing process. Developed on the basis of the application of the theory of volumetric rigidity, a mathematical model of the hydromechanical drive system of the plunger hydraulic cylinder service life test bench made it possible to compare the influence of various design and functional parameters of the elements of the hydromechanical system of the stand on the dynamic performance and energy efficiency of its drive.

1 Introduction

The high cost of energy resources and environmental pollution are becoming more and more urgent global problems that contribute to the development of energy-saving technologies. To reduce the energy consumption of the machine, it is necessary either to increase the efficiency of the components, or to use the energy that is lost during operation by regeneration.

All over the world, energy efficiency and energy conservation are important practical research topics in technological machines and equipment. Reliability is a significant parameter of machines, mechanisms, drives, technological equipment and its component parts, including hydraulic motors. Reliability is checked and confirmed by carrying out resource tests, the results of which reveal the characteristics and properties of materials,

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components and working fluids that are used in the production of hydraulic cylinders and during operation.

One of the practical ways to determine reliability is testing. Resource tests are considered energy-intensive, because it is necessary to carry out tests for a long time, which is stated in the technical specifications or GOST. Durability is laid down by the manufacturer of hydraulic motors in the form of the total total length of the hydraulic cylinder strokes. So, for plunger hydraulic cylinders, reliable operation must be ensured when passing 1500 kilometers of the plunger, which is 57 days or 1388 hours of continuous operation of the hydraulic motor at a speed of 0.3 m /s.

Reliable results of resource tests will be provided by test facilities that will allow testing in conditions close to real operating conditions. These conditions include the spatial location of the test sample and the presence of some external load. The spatial arrangement is achieved due to the design of the stand, the load with the help of loading subsystems. Loading subsystems are usually implemented in the form of hydraulic or mechanical loading devices. These subsystems consume a significant amount of energy resources, which are converted into heat during testing, i.e. energy is not used efficiently.

In their research, scientists Rybak A.T., Zharov V.P., Chukarin A.N. Ustyantsev M.V. propose to solve this problem when testing rotary hydraulic machines using energy recovery. The analysis of the research results showed the energy efficiency of this method. For resource tests of reciprocating hydraulic machines, a hydromechanical drive with energy recovery has been developed. The design of the stand and the scheme proposed in the works allow testing in conditions closest to real operating conditions.

Existing technical solutions in this area have various disadvantages, for example, the lack of automatic control of tests, the need for an additional energy source for the load circuit, low energy efficiency, etc.

The purpose of the work is to describe the methods of calculation and design of the hydromechanical drive system of the service life test bench of plunger hydraulic cylinders through the use of an energy recovery scheme that provides an increase in the energy efficiency of the testing process.

2 Materials and Methods

To solve the tasks, the following methods were used:

– mathematical modeling of the regenerative hydromechanical system was performed using the theory of volumetric rigidity and taking into account the coefficient of volumetric rigidity of hydraulic elements;

– modelling and analysis of the elements of the hydromechanical drive system of the service life test bench of plunger hydraulic cylinders in the SimInTech environment;

– studies of drive kinematics, statics and dynamics of the hydraulic system;

– methods and provisions of analytical, theoretical and experimental mechanics, hydraulics and elasticity theory, numerical methods for solving differential equations.

The object of the study is a hydromechanical drive system of the service life test bench of plunger hydraulic cylinders equipped with the proposed energy recovery system.

The subject of the study is the process and theory of energy recovery during testing of plunger hydraulic cylinders, the influence of the design and functional parameters of the test bench on the energy efficiency of the tests and on its dynamic properties.

3 Results and Discussion

The most effective way of energy saving is a recuperative system of mechanical and hydraulic energy combined when used in a hydromechanical drive, which can significantly reduce the energy consumption of the primary energy source due to the circulation of energy between hydraulic machines. In this case, the primary energy source replenishes the drive system by the amount of losses in hydraulic lines, bearing friction forces in the hubs of the supports, losses in belt gears, etc.

In the process of conducting various tests, including hydraulic volumetric machines, useful work is not performed, therefore, the power consumed by the drive must be reduced as much as possible. To reduce the power consumption of the drive, it is proposed to introduce additional mechanical gears with certain gear ratios into the drive system of the stand, which would connect the drive shafts of rotary-acting machines and the electric motor. Together, the proposed hydro-mechanical drive of the stand provides energy recovery during resource testing of plunger hydraulic cylinders.

There are known designs of regenerative drives for testing hydraulic machines in which, during the testing process, one test machine is a load for another test machine and vice versa [1, 2].

The hydrokinematic scheme of the drive of the service life test bench of plunger hydraulic cylinders with energy recovery without a transfer link is shown in Figure 1. [3, 4]. The stand works as follows. The hydraulic pump is driven by rotation from the shaft of the electric motor. At the outlet of the hydraulic pump, the hydraulic energy of the fluid flow arises, converted from the mechanical energy of the electric motor.

Figure 1 shows a hydrokinematic diagram of a stand for working tests of hydraulic cylinders with a transfer link between the tested cylinders. The hydro-mechanical drive system of the stand consists of two subsystems [5, 6].

The first subsystem consists of a mechanical transmission 6 (rocker arm) mounted on a bed 4, between the tested hydraulic cylinders 5 and 7, which change their functions alternately hydraulic pump-hydraulic motor.

The second subsystem includes an electric motor 13, which is the main source of energy, a hydraulic adjustable pump 1, a hydraulic motor 10, which in turn are interconnected by mechanical gears 12 and 14. Together, hydraulic and mechanical transmission form a regenerative energy-saving system [7].

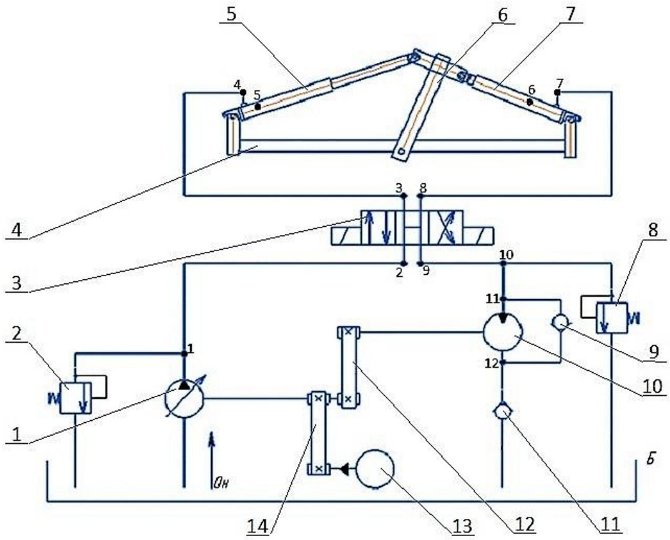

Fig. 1. Hydrokinematic scheme of the stand for resource testing of plunger hydraulic cylinders with energy recovery. *Source: drawn by authors.*

The flow of working fluid along the hydraulic line 1-2-3 enters the hydraulic distributor HD, then through the channel 4-5 into the working cavity of the plunger hydraulic cylinder HC1. The rods of the hydraulic cylinders HC1 and HC2 are mechanically interconnected. Consequently, when the plunger HC1 is extended, the plunger HC2 is retracted. Then the flow of the working fluid enters the input of the hydraulic motor, in which the hydraulic energy of the working fluid is converted into mechanical energy of shaft rotation, the shaft of the hydraulic motor is connected to the mechanical transmission MT, through which the energy is transferred to the shaft of the hydraulic pump HP, where it is combined with the rotational energy of the shaft of the electric motor and again converted by the hydraulic pump into the energy of the RV. When switching sections of the hydraulic distributor HD, the hydraulic cylinders move in the opposite direction, the shaft of the hydraulic motor does not change the direction of rotation.

There is also a transfer link between the tested hydraulic cylinders, which ensures the spatial arrangement of the tested HZ during testing as close as possible to the actual operating conditions. It is in this way that plunger hydraulic cylinders on combine harvesters are located at an angle, serving for lifting and lowering the inclined chamber with a header.

One of the most effective methods of preliminary research of technical objects at present is their mathematical modelling and calculation of expected characteristics [7, 8, 9]. When modelling the hydro-mechanical system of the stand, the following assumptions are made: all mechanical elements of the stand system are considered absolutely rigid; there are no gaps in the hinges; the motor shaft rotation frequency is assumed to be constant; leaks in the hydraulic distributor are neglected. The mathematical model of the proposed stand in Figure 2.1 is based on the theory of volumetric rigidity of the hydraulic system [10, 11]. The essence of the theory is to study the dynamic characteristics of the hydraulic system over time.

To analyse the functioning of the hydromechanical system, as well as to account for energy losses in the hydromechanical system of the proposed hydraulic machine test bench, a mathematical model has been developed [12, 13], according to the theory of volumetric rigidity, the pressure increment *dp*, in time in the allocated volume of the working fluid of any section of the hydraulic system is determined by the formula

$$dp = C_{red\,i}\left(\sum Q_{int_i} - \sum Q_{out_i}\right)dt \tag{1}$$

where $\sum Q_{int}$ is the sum of all instantaneous flow rates of the working fluid included in considered (i–th) volumes of liquid during *dt*;

$\sum Q_{out_i}$ is the sum of all instantaneous flow rates of the working fluid coming from the considered (i-th) volume of fluid during *dt*;

C_{red_i} is the reduced coefficient of volumetric stiffness of the selected section of the hydraulic system.

To determine the mutual relationship of the speeds of movement of the plungers of hydraulic cylinders, consider the kinematic scheme of the mechanical system of the stand, shown in Figure 2.

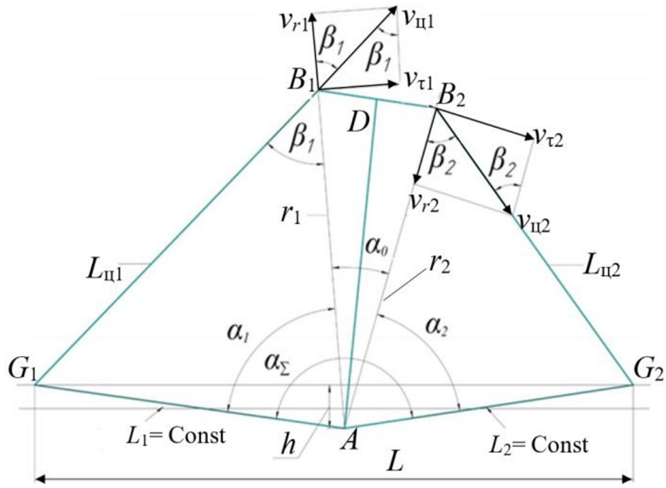

Fig. 2. Kinematic diagram of the mechanism of motion transmission between the test cylinders, *Source: drawn by authors.*

The diagram shown in Figure 2 consists of the following elements and interface points. The hydraulic cylinder liners 5 (Lc1) and 7 (Lc2) are mounted respectively at the hinge points G1 and G2, and their plungers are pivotally connected to the rocker arm 6 at points B1 and B2, which has an axis of rotation at point A.

The result of previously conducted experiments is the possibility of using energy recovery. Measurements have shown that energy recovery from potential energy is possible in both hydraulic and electrical energy storage systems.

The proposed version of the energy efficiency assessment cannot be applied to the GMP test bench for plunger hydraulic cylinders, because in the systems described, the recovered energy returns to the primary source, and in the test bench, energy is reused between the tested hydraulic machines.

In his work, Ustyantsev M.V. to assess the energy efficiency of the recuperative GMP system of the test bench for rotary hydraulic machines, proposed a test cost coefficient that is equal to the ratio of the power expended to the power on the tested hydraulic machines:

$$k_{test} = \frac{N_{cons}}{N_{test}} \tag{2}$$

where N_{cons} is the power consumed by the electric motor;

N_{test} – power on the tested machines.

Therefore, the lower the cost factor, the more energy efficient the regenerative drive is.

In this study, to assess the energy efficiency of a hydromechanical drive, it is proposed to introduce the test efficiency coefficient equation (3), which is the ratio of the power on the tested hydraulic machine to the power expended during its testing. The higher the energy efficiency coefficient of the tests, the greater the power on the tested machines, therefore, in order for k_{efi} to be greater than one (energy saving), the power on the energy source should be as small as possible. It is possible to implement this condition only with the use of additional mechanical connections introduced in the drive with certain gear ratios.

The efficiency of testing hydraulic cylinders with energy recovery can be estimated in two ways: by the instantaneous value of the efficiency coefficient and by the average value of the test efficiency coefficient.

The instantaneous value of the test efficiency coefficient is calculated by the formula

$$k_{efi} = \frac{N_{test}}{N_{en.s.}} \tag{3}$$

where N_{test} is the power on the tested hydraulic cylinder at the i moment of time, W;
$N_{en.s.}$ – the power at the input of the electric motor at the i moment of time, W.
The average value of the test efficiency coefficient is determined by the formula

$$k_{t.ef.} = \frac{W_{test}}{W_{en.s.}} \tag{4}$$

where W_{test} – the energy that has passed through the tested hydraulic machine since the start of the tests at the time under consideration, J;

$W_{en.s.}$ – the energy consumed by the energy source since the start of the tests at the time under consideration, J.

According to the above material from equations (3) and (4), equations (5) and (6) can be written to determine the energy efficiency coefficient of specific tests, namely resource tests of plunger hydraulic cylinders, and an additional introduced link will be the developed recuperative system.

Then, the instantaneous value of the test efficiency coefficient of plunger hydraulic cylinders is calculated by the formula

$$k_{efi} = \frac{N_{ci}}{N_{eli}} \tag{5}$$

where $N_{цс}$ is the power on the tested hydraulic cylinder at the *i* moment of time, W;
N_{eli} – the power at the input of the electric motor of the hydraulic pump drive at the i moment of time, W.

The average value of the test efficiency coefficient of plunger hydraulic cylinders is determined by the formula

$$k_{ef} = \frac{W_{test}}{W_{el}} \tag{6}$$

where W_{test} is the energy that has passed through the tested hydraulic cylinder since the start of the tests at the time under consideration, J;
W_{el} is the energy consumed by the hydraulic pump energy source (electric motor) from the start of the tests to the time under consideration, J.
Figure 2 shows a graph comparing the instantaneous and average values of the test efficiency coefficient.

During the resource tests, the hydraulic cylinder plungers stop at the end points of the stroke and reverse (change of direction of movement) occurs, at this point the level of the test efficiency coefficient goes to zero, therefore, it is advisable to conduct further analysis based on the average value of the efficiency coefficient.

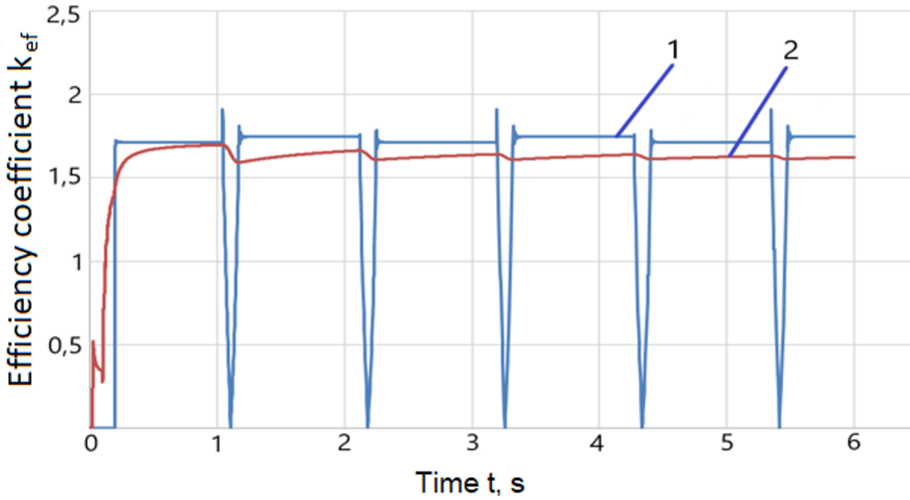

Fig. 2. Efficiency coefficient: 1 – the instantaneous value of the efficiency coefficient; 2 – the average value of the efficiency coefficient. *Source: drawn by authors.*

It can be seen from the graph in Figure 2 that the average value of the efficiency coefficient is less than instantaneous (except for the reverse time).

This is due to the reduction to zero of the power on the tested hydraulic cylinders at the moment of changing the direction of their movement, when reaching the extreme position. Hence, it can be concluded that in order to increase the efficiency of tests, it is advisable to minimise the reverse switching time, which, however, will also affect the dynamic properties and indicators of the system.

The hydraulic elements interconnected in the hydraulic system are a structure where the working fluid is the RV. During the operation of such a system, the physical, structural parameters of the components and the properties of the RV are not constant, there are some changes due to the influence of various physical processes. The design parameters of the elements are: the rotational speed of the hydraulic motor, the power consumed, the force developed, speed, displacement, i.e. parameters that affect the dynamic process in the hydraulic system. The parameters of the working fluid include pressure drop, flow rate, pressure. Graphical time dependences obtained of the above parameters allow us to investigate the dynamic properties of the hydraulic system [15...19].

The theoretical analysis of the functioning of the stand model for resource testing of plunger hydraulic cylinders allowed us to analyse the durability of cylinders in various test conditions, as well as identify potential problems or failures, modes that may arise during testing.

In addition, the experiment conducted on bench equipment established the correctness and operability of the regenerative system of the hydromechanical drive of the service life test bench of plunger hydraulic cylinders. The accepted methods of processing and collecting the measured parameters of the experimental setup confirm the correctness of the mathematical model. [18-20].

4 Conclusion

A schematic diagram of a hydromechanical drive of a stand for resource testing of plunger hydraulic cylinders with energy recovery with a transfer link between the tested hydraulic cylinders has been developed. The proposed scheme makes it possible to carry out resource tests of hydraulic cylinders in conditions close to the actual operating conditions of the hydraulic motor and with the possibility of creating a given level of loads.

The proposed mathematical model of the hydromechanical drive of the service life test bench of plunger hydraulic cylinders allows us to evaluate the energy efficiency of the regenerative drive. [21...23].

Mathematical modeling of the hydro-mechanical drive system of the stand makes it possible to evaluate the quantitative and qualitative influence of various structural and functional parameters of the elements of the hydro-mechanical system on the main functional, including dynamic indicators.

To assess the energy efficiency of hydraulic tests, an instantaneous test efficiency coefficient is proposed, which is defined as the ratio of the power on the tested hydraulic machine to the power expended, i.e. the power at the input of the energy source. The average value of the energy efficiency coefficient is defined as the ratio of the energy that has passed through the tested hydraulic machine since the beginning of the tests at the time under consideration to the energy consumed by the energy source since the beginning of the tests at the time under consideration. [24].

Developed on the basis of the application of the theory of volumetric rigidity, a mathematical model of the hydromechanical drive system of the plunger hydraulic cylinder service life test bench made it possible to compare the influence of various structural and functional parameters of the elements of the hydromechanical system of the stand on the dynamic performance and energy efficiency of its drive already at the design stage. The introduced test efficiency coefficient makes it possible to evaluate energy savings when testing not only hydraulic machines, but also any other hydraulic devices.

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