International Journal of Mechatronics and Applied Mechanics
2026, Issue 25, Vol. II

INVESTIGATION OF DYNAMIC CHARACTERISTICS OF A HYDRAULIC DRIVE FOR LOADING AND UNLOADING MACHINES

Dmytro Lozinskyi [0000-0002-1077-1621], Oleh Piontkevych [0000-0002-3460-8060], Olha Serdiuk [0009-0001-0082-2990]
Department of Mechanical Engineering Technologies and Automation
Vinnytsia National Technical University, Khmelnytske shose, 95, Vinnytsia, Ukraine, 21021
E-mail(s): lozinskiy_dmitriy@vntu.edu.ua, piontkevych@vntu.edu.ua, serdyuk0904@vntu.edu.ua

Abstract - Mobile and technological machines operating under relatively high loads commonly use hydraulic drives because of their high power density. The performance and functional capabilities of hydraulic-drive components are therefore essential for the operating properties of the machine as a whole. This paper analyzes current trends in the development of hydraulic-drive components and proposes the use of independent metering valves to improve system flexibility. A general concept of a hydraulic drive for mobile machines used in loading and unloading operations is presented. Proportional directional-control elements are proposed for each chamber of the working actuator. This arrangement enables independent metering at the inlet and outlet of the hydraulic cylinder and allows selected operations to be performed using the energy accumulated in the actuator-load system. At the same time, pilot-operated check valves provide sealing of the working chambers of the hydraulic system. A calculation scheme was developed, and a mathematical model was formulated to investigate working processes in the hydraulic drive using MATLAB Simulink. The model includes continuity equations for the hydraulic lines and force-balance equations for the moving components of the hydraulic system. The influence of the main design parameters of the pilot-operated check valve on transient processes in the hydraulic drive is investigated. Parameter ranges that improve the dynamic characteristics of the system are determined. The obtained results can be used by specialists involved in the design of hydraulic equipment and drive systems for mobile and technological machines.

Keywords: Hydraulic drive, Independent metering system, Pilot-operated check valve, Mathematical model, Transient processes, Dynamic characteristics.

1. Introduction

A hydraulic drive is an integral part of technological and mobile machines for various purposes when operation under relatively high loads is required. It provides considerable useful power with comparatively low energy and mass indicators. This type of drive is used in many mobile machines, particularly those performing loading and unloading operations [1, 2]. A specific feature of such machines is the combination of working operations under significant loads, the need for smooth and sufficiently accurate load control, and the ability to hold the load in a specified position for the required period of time [3].

Many mobile loading and unloading machines still use discrete-action hydraulic equipment, which reduces the quality of machine operation and increases energy consumption [4]. Therefore, studies aimed at analyzing the design parameters of new hydraulic-drive equipment and reducing these disadvantages are relevant.

2. Literature Review

A considerable number of studies have addressed the improvement of hydraulic equipment and its components. Productivity, controllability, flexibility, and economic efficiency are important aspects of mobile machines based on hydraulic drives [5].

Because hydraulic drives have been used for a long time, many circuit layouts, designs, and variants of shut-off and directional-control equipment have been developed. Among the current requirements for mobile machines, reducing energy-resource consumption is especially important; this creates the need to study and improve the energy efficiency of hydraulic drives. Reference [6] provides a

dx.doi.org/10.17683/ijomam/issue25/v2.4

classification of hydraulic-system developments and their energy efficiency in performing the corresponding tasks.

Reference [7] considers the operating efficiency of hydraulic drives working with a passive load and with the function of holding the actuator position. The authors proposed improving hydraulic-drive efficiency by using self-contained electrohydraulic cylinders capable of passive load holding. Such a hydraulic drive is effective; however, it requires a complex design with an increased number of hydraulic units, which substantially reduces the flexibility of the hydraulic system.

The authors of [8] proposed improving the flexibility and functionality of a hydraulic drive by using valves with independent metering. One of the main features of this principle is the ability to control the inlet and outlet flows of a hydraulic actuator independently.

Reference [9] presents the advantages and disadvantages of using independent metering valve systems. The main advantage of such systems is the possibility of regeneration and energy-saving operation through independent control of the inlet and outlet flows. The authors emphasize improved control of cylinder speed and position stability, as well as broader functional capabilities compared with conventional single-spool control. At the same time, the configuration capabilities of the hydraulic drive as a whole and the control possibilities for its operating parameters are expanded. Different configurations of independent metering valve systems are presented; they differ from conventional systems in both design and functional characteristics. The proposed configurations are intended to reduce such disadvantages as design complexity, control complexity, and the influence of different operating modes on actuator speed.

In [10], independent metering valve systems were compared with conventional load-sensing hydraulic systems in terms of energy consumption. The results confirm the improved energy efficiency of hydraulic systems with independent metering at the inlet and outlet of the hydraulic actuator, which is particularly important for machines with high energy consumption.

Although independent metering valve systems are more complex than traditional systems, their improved functionality provides better possibilities for both performing and controlling working processes. The authors of [11] investigated the application of an independent metering valve system to an excavator hydraulic drive. The study examined the operating and control features of the main excavator hydraulic cylinder with the aim of reducing throttling losses. This hydraulic cylinder operates under a considerable load that can change its direction; during part of the working cycle, operations may also be performed with a passive load. Owing to the broader functionality of independent metering valve systems, the authors proposed a hybrid strategy for cylinder speed and position control that accounts for different operating modes. The results improved the accuracy of working operations and reduced losses in certain modes, for example during operations with a passive load.

The broad possibilities for controlling hydraulic-actuator flows reduce the energy required for certain working operations by using accumulated energy. The authors of [12] proposed applying an independent metering valve system to the loaded hydraulic cylinder of an excavator hydraulic drive. This hydraulic system makes it possible to perform operations using accumulated potential energy, thereby reducing the overall energy demand of the working cycle.

The performance of hydraulic drives in mobile and technological machines can be improved through advanced control algorithms combined with different hydraulic units. Reference [13] studies a new hydraulic system for electrohydraulic control of a front-loader bucket using closed-center hydraulic equipment. The developed control algorithms, together with industrial controllers, were tested on a medium-size loader. The results confirm a positive effect despite the increased complexity of the hydraulic system.

Reference [14] describes features of designing new hydraulic equipment for technological machines. These approaches include developing a mathematical model, solving it, and performing subsequent analysis. An important design aspect is optimization of transient processes in a hydraulic drive under variable load. This is because the design parameters of hydraulic equipment substantially affect the dynamic characteristics of the hydraulic drive, with changes reaching 70-100% relative to the maximum value.

The authors of [15] proposed a mathematical model of a hydraulic drive invariant to alternating load direction. Special hydraulic equipment or counterbalance valves are used to counteract uncontrolled overrunning loads. A disadvantage of such a hydraulic drive is the presence of local pressure losses of up to 2 MPa; as a result, the positioning accuracy of the working member does not exceed 8%.

Modern design calculations for new hydraulic equipment should be performed with simulation of working-fluid flow through its channels [16]. In particular, [17] presents the improvement of an existing three-dimensional model of hydraulic units using flow simulation of the working fluid. The obtained results reduce hydraulic-pressure losses in the directional control valve. However, the influence of the changes made to the three-dimensional model on the transient dynamics of the hydraulic drive remains unresolved.

Simulation of working-fluid flow in hydraulic equipment makes it possible to calculate local pressure losses in hydraulic-drive channels [18] and reduce them by providing smooth transitions, casting radii, and appropriate channel diameters. The obtained calculations improve the accuracy of the hydraulic-drive mathematical model. However, before a three-dimensional model of hydraulic equipment is created, preliminary calculations and recommendations for selecting design parameters are required.

Recent experimental studies aimed at achieving high accuracy in hydraulic-drive equipment are considered in [19]. The reported results make it possible to improve the accuracy of the mathematical model by accounting for the main environmental factors. In addition, the authors of [20] experimentally determined the required dependencies for parameters of reduced-scale hydraulic-drive models. These parameters improve mathematical models; however, manufacturing an experimental prototype of hydraulic equipment requires preliminary calculations and recommendations for selecting its design parameters.

The literature analysis shows that improving the functionality and performance of hydraulic drives remains a relevant problem. Hydraulic drives with independent metering have been developed substantially; nevertheless, most known solutions implement independent flow control by means of structurally complex multistage valves, in which flow metering, motion-direction control, and chamber sealing functions may be combined in one element.

This paper proposes a different structural approach to constructing a hydraulic drive with independent metering. The approach is based on functional separation of the elements: several independent directional-control elements are used to control the working-fluid flows, while separate pilot-operated check valves are used to ensure sealing of the working chambers. The proposed hydraulic-drive structure differs from known solutions in its circuit layout and in the interaction of the elements. Table 1 compares it with typical hydraulic-drive solutions used in mobile machines.

Therefore, it must be analyzed with regard to the dynamic processes occurring during operation. This requires mathematical modeling to investigate the dynamic characteristics of the proposed hydraulic drive and to determine the influence of the design parameters of pilot-operated check valves in transient operating modes.

Table. 1 Comparison of the proposed hydraulic-drive configuration with existing solutions

Configuration	Hydraulic elements	Circuit complexity	Functional capabilities	Energy efficiency	Dynamic-performance aspect
Conventional single-spool valve system	One main directional valve, actuator, auxiliary check/load-holding elements	Low	Coupled inlet and outlet flow control; limited flexibility	Limited by throttling losses	Depends mainly on spool dynamics and load variation
Classical independent metering system [9, 10]	Several metering edges/valves, controller, actuator, auxiliary elements	High	Independent inlet/outlet metering; regeneration and flexible control are possible	High potential, especially under overrunning loads	Strongly dependent on valve coordination and control algorithm
Electrohydraulic cylinder with passive load holding [7]	Pump/motor unit, cylinder, holding valves and control components	High	Compact load holding and local actuation	Reduced losses in selected modes	Defined by integrated actuator and control architecture
Proposed configuration	Separate proportional directional-control elements and pilot-operated check valves for chamber sealing	Moderate	Independent metering with functional separation of metering and sealing	Energy-saving modes using accumulated load energy are possible	Design parameters of pilot-operated check valves directly affect overshoot, oscillation index, and settling time

3. Purpose and Objectives

The purpose of this study is to investigate and determine the influence of the design parameters of pilot-operated check valves in the hydraulic drive of a loading and unloading machine with independent metering of the working-fluid flows.

Achieving this purpose makes it possible to determine rational values of the design parameters of hydraulic-equipment elements and to formulate recommendations for designing three-dimensional and full-scale models of hydraulic equipment for hydraulic drives with independent metering.

To achieve the stated purpose, the following objectives were set:

- to develop and substantiate the structural circuit of a hydraulic drive with independent metering based on the use of several directional-control elements and pilot-operated check valves, considering stable operation, functional capabilities, and energy efficiency;
- to develop a calculation scheme and formalize a mathematical model for analyzing transient processes in the hydraulic drive;
- to investigate the influence of the design parameters of pilot-operated check valves on the dynamic characteristics of the hydraulic drive and formulate recommendations for their selection.

4. Materials and Methods

Based on the analysis of previous studies, a general concept of a hydraulic drive for mobile machines used in loading and unloading operations is proposed. The basic hydraulic circuit of this drive is shown in Fig. 1.

To study the machine hydraulic drive and analyze the influence of design parameters on its dynamic characteristics, a calculation scheme was developed (Fig. 2). On the basis of this scheme, the mathematical model (1)-(8) was formulated to describe the processes in the machine hydraulic drive.

When creating the mathematical model (1)-(8), typical assumptions used in hydraulic-drive models were adopted [4, 15]. The hydraulic system was considered as a lumped-parameter system, which is acceptable for the relatively short hydraulic lines and low-frequency transient processes analyzed in this study. Cavitation-free operating modes were assumed because the investigated operating range does not involve pressure reduction below the vapor pressure of the working fluid.

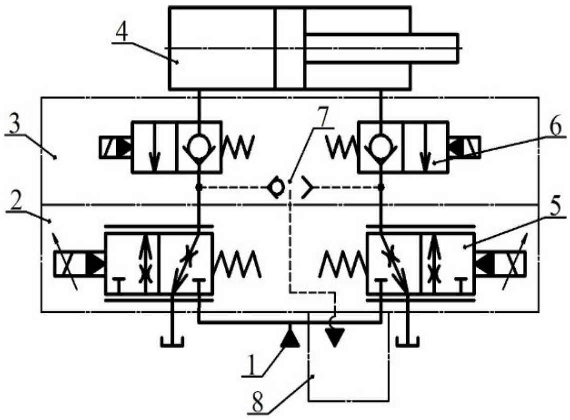

Figure 1: Basic hydraulic circuit: 1 - pressure line; 2 - directional-control section; 3 - sealing section; 4 - hydraulic cylinder; 5 - proportional directional-control element; 6 - pilot-operated check valve; 7 - OR logic valve; 8 - working-fluid supply control element

The working-fluid temperature was considered constant during each simulation, since the analyzed transient processes are short and do not cause a significant change in the thermal state of the system. The discharge coefficients through throttles and spool elements were also assumed to be constant. This simplifies the model, although changes in viscosity and Reynolds number may affect the calculated working-fluid flow rates under operating conditions outside the considered range.

Wave processes in the hydraulic system and distributed pressure losses in the hydraulic lines were neglected. This assumption is acceptable because the main pressure drops are expected at the metering elements and pilot-operated check valves.

The compliance coefficient of the working fluid was considered as an average value for the investigated pressure range. Internal leakages in the hydraulic-drive elements were described as proportional quantities, which is sufficient for preliminary dynamic analysis.

Unlike known models, the proposed mathematical model accounts for the interaction between proportional spool-type directional-control elements and pilot-operated check valves under independent metering modes. This enables investigation of the dynamic characteristics of the hydraulic drive in different operating modes.

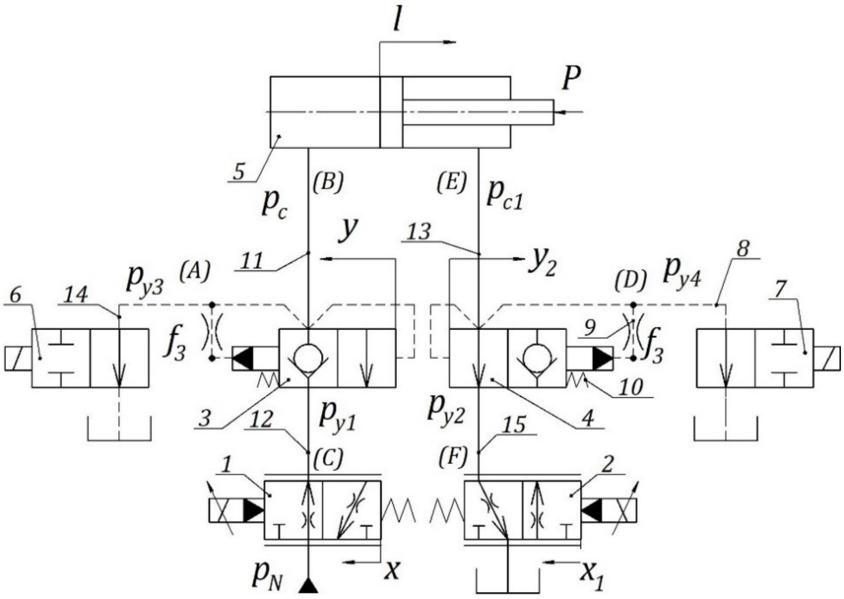

Figure 2: Calculation scheme: 1, 2 - proportional directional-control elements; 3, 4 - valve elements of the pilot-operated check valves; 5 - hydraulic cylinder; 6, 7 - electrohydraulic servovalves controlling the check valves; 8, 14 - hydraulic lines at the hydraulic-cylinder outlet; 9 - throttle; 10 - spring; 11, 13 - hydraulic lines at the hydraulic-cylinder inlet; 12, 15 - hydraulic lines at the outlets of the directional-control elements

The mathematical model (1)-(8) includes continuity equations for hydraulic lines 11-15 and force-balance equations for the moving hydraulic-drive elements 3-5. The general system of equations for the hydraulic drive is presented below:

$$\mu \cdot \pi \cdot d_X \cdot x \cdot \sin\alpha \cdot \sqrt{\frac{2\cdot|P_N - P_{y1}|}{\rho}} \cdot sign(p_N - P_{y1}) = \mu \cdot \sqrt{\frac{2\cdot|P_{y1} - P_C|}{\rho}} sign(p_{y1} - p_c) \cdot \left[\frac{\pi}{2}\cdot(y \cdot \sin\gamma + 2 \cdot d_{y1}) \cdot y' \cdot \sin\frac{\gamma}{2}\right] + \beta \cdot W_C \cdot \frac{dP_{y1}}{dt}, \tag{1}$$

$$\mu \cdot \left[\frac{\pi}{2}\cdot(y \cdot \sin\gamma + 2 \cdot d_{y1}) \cdot y \cdot \sin\frac{\gamma}{2}\right] \cdot \sqrt{\frac{2\cdot|p_{y1} - p_C|}{\rho}} \cdot sign(p_{y1} - p_c) = \frac{dl}{dt}\cdot\frac{\pi \cdot D_C^2}{4} + \mu \cdot f_3 \cdot \sqrt{\frac{2\cdot|p_c - p_{y2}|}{\rho}} \cdot sign(p_c - p_{y2}) + \beta \cdot W_B \cdot \frac{dp_C}{dt}, \tag{2}$$

$$F_{C1} \cdot \frac{du}{dt} = \mu \cdot \left[\frac{\pi}{2}\cdot(y_1 \cdot \sin\gamma + 2 \cdot d_{y1}) \cdot y_1 \cdot \sin\frac{\gamma}{2}\right] \cdot \sqrt{\frac{2\cdot p_{c1}}{\rho}} + \mu \cdot f_3 \cdot \sqrt{\frac{2\cdot|p_{c1} - p_{y3}|}{\rho}} \cdot sign(p_{c1} - p_{y3}) + \mu \cdot f_3 \cdot \sqrt{\frac{2\cdot|p_{c1} - p_{y4}|}{\rho}} \cdot sign(p_c - p_{y1}) + \beta \cdot W_E \cdot \frac{dP_{c1}}{dt}, \tag{3}$$

$$\mu \cdot \left[\frac{\pi}{2}\cdot(y_1 \cdot \sin\gamma + 2 \cdot d_{y1}) \cdot y_1 \cdot \sin\frac{\gamma}{2}\right] \cdot \sqrt{\frac{2\cdot|p_{c1} - p_{y3}|}{\rho}} \cdot sign(p_{C1} - p_{y3}) = \beta \cdot W_F \cdot \frac{dp_{y2}}{dt} + \mu \cdot \pi \cdot d_X \cdot x_1 \cdot \sin\alpha \cdot \sqrt{\frac{2\cdot|p_{y2}|}{\rho}}, \tag{4}$$

$$\mu \cdot f_3 \cdot \sqrt{\frac{2\cdot|p_c - p_{y2}|}{\rho}} \cdot sign(p_c - p_{y1}) + \mu \cdot f_3 \cdot \sqrt{\frac{2\cdot|p_{C1} - p_{y2}|}{\rho}} \cdot sign(p_{C1} - p_{y2}) = \mu \cdot \left[\frac{\pi}{2}(s \cdot \sin\delta + 2 \cdot d_{y2}) \cdot s \cdot \sin\frac{\delta}{2}\right]\sqrt{\frac{2p_{y2}}{\rho}} + \beta \cdot W_A \cdot \frac{dp_{y3}}{dt} + \beta \cdot W_D \cdot \frac{dp_{y3}}{dt}, \tag{5}$$

$$m_y \frac{dV_y}{dt} = p_{y1} \cdot F_{y1} - p_{y2} \cdot F_y + p_c(F_y - F_{y1}) - c_y \cdot (H_y + y) - b_y \frac{dy}{dt} - T_y, \tag{6}$$

$$m_y \frac{dV_{y1}}{dt} = p_{y3} \cdot F_{y1} - p_{y4} \cdot F_y + p_{c1}(F_y - F_{y1}) - c_y \cdot (H_y + y_1) - b_y \frac{dy_1}{dt} - T_{y1} \cdot sign\frac{dy_1}{dt}, \tag{7}$$

$$m_C \frac{dV_l}{dt} = p_c \cdot F_C - p_{c1} \cdot F_{C1} - P - b_C \frac{dl}{dt} - -T_C \cdot sign\frac{dl}{dt}. \tag{8}$$

The symbols used in the mathematical model (1)-(8) are summarized in Table 2. The correspondence between pressure variables, hydraulic lines, and components follows the calculation scheme shown in Fig. 2.

Table.2 Nomenclature used in the mathematical model

Symbol	Definition	SI unit
x, x_1	Displacement coordinates of proportional directional-control elements 1 and 2	m
y, y_1	Displacement coordinates of the valve elements of pilot-operated check valves 3 and 4	m
l	Displacement coordinate of the rod of hydraulic cylinder 5	m
s, s_1	Displacement coordinates of servovalves 6 and 7 controlling the check valves	m
p_N	Pressure in the pressure line	Pa
p_{y3}, p_{y4}	Pressure in hydraulic lines 14 and 8	Pa
p_c	Pressure in hydraulic line 8	Pa
p_{c1}	Pressure in hydraulic line 13	Pa
p_{y1}, p_{y2}	Pressures in hydraulic lines 12 and 15	Pa
P	Load force acting on the rod of hydraulic cylinder 5	N
d_x	Spool diameter of directional-control elements 1 and 2	m
d_y	Diameter of the valve elements of pilot-operated check valves 3 and 4	m
d_{y1}	Diameter of the inlet channels of pilot-operated check valves 3 and 4	m
d_{y2}	Diameter of servovalves 6 and 7	m
α	Inclination angle of the working edges of the spools of directional-control elements 1 and 2	rad
γ	Inclination angle of the working valve elements of pilot-operated check valves 3 and 4	rad
δ	Inclination angle of the working edge of servovalves 6 and 7	rad
f_3	Opening area of the working window of throttle 8	m^2
F_C	Cap-end piston area of hydraulic cylinder 5	m^2
F_{C1}	Rod-side piston area of hydraulic cylinder 5	m^2
F_{k1}	Area of the inlet channels of pilot-operated check valves 3 and 4	m^2
c_y	Stiffness of spring 10	N/m
H_y	Initial compression of spring 10	m
W_A, W_B, W_C	Fluid volumes in hydraulic lines 8, 11, and 12	m^3
W_E, W_D, W_F	Fluid volumes in hydraulic lines 13, 14, and 15	m^3
m_y	Mass of the spools of pilot-operated check valves 3 and 4	kg
m_C	Mass of the hydraulic-cylinder rod	kg
b_y	Viscous damping coefficient of the valve elements of pilot-operated check valves 3 and 4	N · s/m
b_C	Viscous damping coefficient of the hydraulic-cylinder rod	N · s/m
T_y, T_{y1}	Friction forces	N
T_C	Friction force acting on the hydraulic-cylinder rod	N
ρ	Working-fluid density	kg/m^3
μ	Discharge coefficient	-
β	Coefficient accounting for the total deformation of the gas-liquid mixture and rubber-metal hoses	Pa^{-1}

The mathematical model was solved numerically using MATLAB Simulink, which was applied only as a tool for integrating the system of differential equations. During simulation, the second-order Rosenbrock method (ode23s), recommended for hydraulic systems [14], was used.

The main simulation settings required for reproducibility are summarized in Table 3.

Table.3 Simulation parameters

Parameter	Value	Unit/description
Software and solver	MATLAB Simulink; ode23s	-
Simulation time	0.1	s
Fixed geometric parameters	$d_x = 20 \cdot 10^{-3}$; $d_y = 28 \cdot 10^{-3}$; $d_{y1} = 20 \cdot 10^{-3}$; $d_{y2} = 3 \cdot 10^{-3}$	m
Working-fluid and flow coefficients	$\rho = 900$; $\mu = 0.7$; $\beta = 1 \cdot 10^{-9}$	kg/m^3; -; Pa^{-1}
Spring stiffness	$c_y = 5 \cdot 10^2$	N/m
Pressure and supply flow	$p_N = (10...100) \cdot 10^5$; $Q_N = 1.67 \cdot 10^{-3}$	Pa; m^3/s
Investigated initial spring compression	$H_y = (0.1...20) \cdot 10^{-3}$	m
Investigated throttle opening area	$f_3 = (0.1...10) \cdot 10^{-6}$	m^2
Investigated viscous damping coefficient	$b_y = 10...40$	kg/s
Initial pressures*	$p_{y1}, p_{y2}, p_{y3}, p_{y4}, p_{c,}, p_{c1} = (0..80) \cdot 10^5$	Pa
Initial displacements*	$x, x_1, s, s_1 = (0..4) \cdot 10^{-3}$	
Initial displacements*	$y, y_1, l = (0..6) \cdot 10^{-3}$	m

** The initial conditions were set depending on the conditions of the process being modeled.*

5. Research

5.1. Analysis of the Basic Hydraulic Circuit

The basic hydraulic circuit (Fig. 1) implements the functional separation of elements responsible for flow control and sealing of the working chambers. The use of separate proportional directional-control elements for each chamber of the hydraulic cylinder, in combination with pilot-operated check valves, creates conditions for independent control of the inlet and outlet flows of the working fluid. This structure enables motion modes that use the accumulated energy of the load and reduce energy losses without complicating the hydraulic-drive design.

The basic hydraulic circuit (Fig. 1) includes pressure line 1, directional-control section 2, sealing section 3, and hydraulic cylinder 4. Proportional directional-control elements 5 are proposed to regulate displacement and improve load controllability, while pilot-operated check valves 6 ensure sealing of the working chambers of hydraulic cylinder 4. OR logic valve 7 provides access of working pressure to working-fluid supply control elements 8 for pressure line 1.

A separate directional-control element 5 and pilot-operated check valve 6 are intended for each working chamber of hydraulic cylinder 4. The use of several independent directional-control elements makes it possible to connect one chamber of the actuator directly to the tank and move the working member by using accumulated energy. In this case, pump pressure can be maintained at a minimum level, reducing energy consumption. This approach allows loading and unloading operations to be performed using the potential energy of the raised load [6, 7].

The proposed basic hydraulic circuit differs from a conventional independent metering valve system by using fewer elements while providing similar functional capabilities. It is based on standardized components, which substantially improves maintainability and serviceability.

5.2. Results of Solving the Mathematical Model of the Hydraulic Drive

Based on the calculation scheme (Fig. 2) and the solved mathematical model (1)-(8), transient processes in the hydraulic system were investigated under dynamic operating modes. Studying the dynamics of transient processes in the machine hydraulic drive makes it possible to observe the system state at different moments of the working cycle and to analyze the influence of the corresponding parameters on dynamic characteristics.

During the investigation of the hydraulic-drive dynamic characteristics, changes in its design parameters were considered: the initial compression of springs 10 of the pilot-operated check valves, H_y, and the opening area of the working windows of throttles 9, f_3. Parameters were varied within the ranges shown in Table 3. The influence of the viscous damping coefficient of the valve elements was also considered, since this coefficient depends substantially on the clearances formed between the elements, as well as on the temperature and type of working fluid (ranges shown in Table 3).

The stable operating region of the developed machine hydraulic drive was determined according to its design parameters. In addition, the influence of pilot-operated check-valve parameter selection on transient processes in the machine hydraulic drive was recorded. Examples of the influence of selected design parameters on the transient response are shown in Figures 3 and 4.

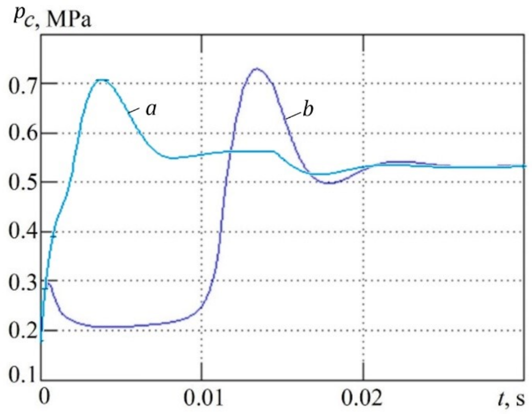

Figure 3: Transient pressure processes for p_c at the initial compression of the valve spring H_y: a - 5 mm; b - 10 mm

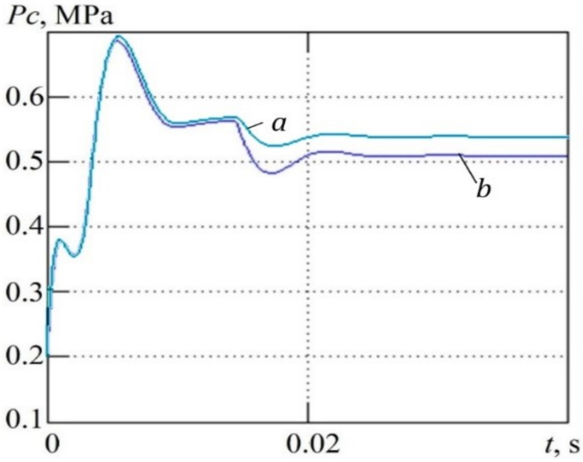

Figure 4: Transient pressure processes for p_c at the throttle opening area f3: a - 4 mm2; b - 8 mm2.

Experimental validation of the transient pressure processes was carried out on the laboratory hydraulic test rig shown in Fig. 5.

The rig includes a hydraulic power unit, an adjustable loading unit, the investigated hydraulic equipment, and a measurement-and-recording system. The power unit contains a vane charging pump with max pressure 6.3 MPa and nominal flow $2.0 \cdot 10^{-3}$ m^3/s and axial-piston pumps with max pressure 32 MPa and nominal flow $2.0 \cdot 10^{-3}$ m^3/s [21].

Figure 5: Laboratory hydraulic test rig

The experimental load was set by an adjustable throttle and lever. Pressure was measured by reference gauges and strain-gauge pressure sensors; the pressure ranges were 0...3 MPa and 0...25 MPa, depending on the measured line, with pressure-sensor accuracy up to +/-1.6%. Flow rate, displacement, and speed were monitored using a hydraulic motor, a dial indicator, and an inductive displacement sensor. The analog signals were recorded by an analog-to-digital converter and a PC-based acquisition system; each operating condition was repeated at least three times.

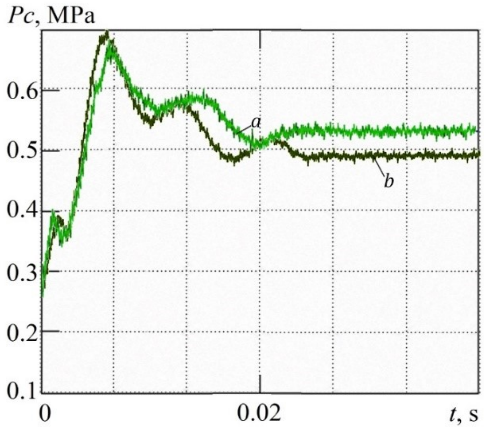

Figure 6: Transient pressure processes for p_c obtained during experimental studies at the throttle opening area f_3: a - 4 mm^2; b - 8 mm^2.

The obtained dependencies make it possible to analyze the course of transient processes and evaluate their dynamic characteristics, namely overshoot sigma, oscillation index *K*, and transient time t_p. Pressure p_c was used as the measured quantity.

The agreement between numerical and experimental results was estimated using the relative difference $\Delta=|X_{exp} - X_{sim}|/ X_{exp} \cdot 100\%$, with the values read from the plotted curves in Fig. 4 and Fig. 6.

The quantitative agreement between the numerical and experimental pressure responses was evaluated from the curves in Fig. 4 and Fig. 6. The comparison was based on the peak pressure $p_{c,max}$, overshoot sigma, oscillation index *K*, and settling time t_p.

The relative approximate differences estimated from Fig. 4 and Fig. 6 are as follows: Δ ($p_{c,max}$) is about 5-7%, Δ (σ) is about 14%, Δ (*K*) is about 16.5%, and Δ (t_p) does not exceed about 15%.

Thus, the comparison confirms an acceptable quantitative agreement between the model and experiment for the analyzed data.

The studies (see Figs. 3-7) showed that the initial compression of the pilot-operated check-valve spring, the opening area of the throttle elements, and the viscous damping coefficient significantly affect the character of transient processes. In particular, certain combinations of these design parameters lead to oscillatory or unstable operating modes, which limits the admissible range of their selection.

5.3. Results of Studying Transient Processes in the Hydraulic Drive

The stable operating region of the machine hydraulic drive was analyzed (Fig. 7, a).

Unstable transient processes limit the investigated range of hydraulic-drive design parameters to f_3 = 1...8 · 10^{-6} m^2 and H_y = 5...12 mm.

The influence of design-parameter values on the dynamic characteristics of the hydraulic drive is nonlinear and parameter-dependent. In other words, the degree of influence on different dynamic characteristics of the hydraulic drive may vary within different limits (Fig. 7, b-d).

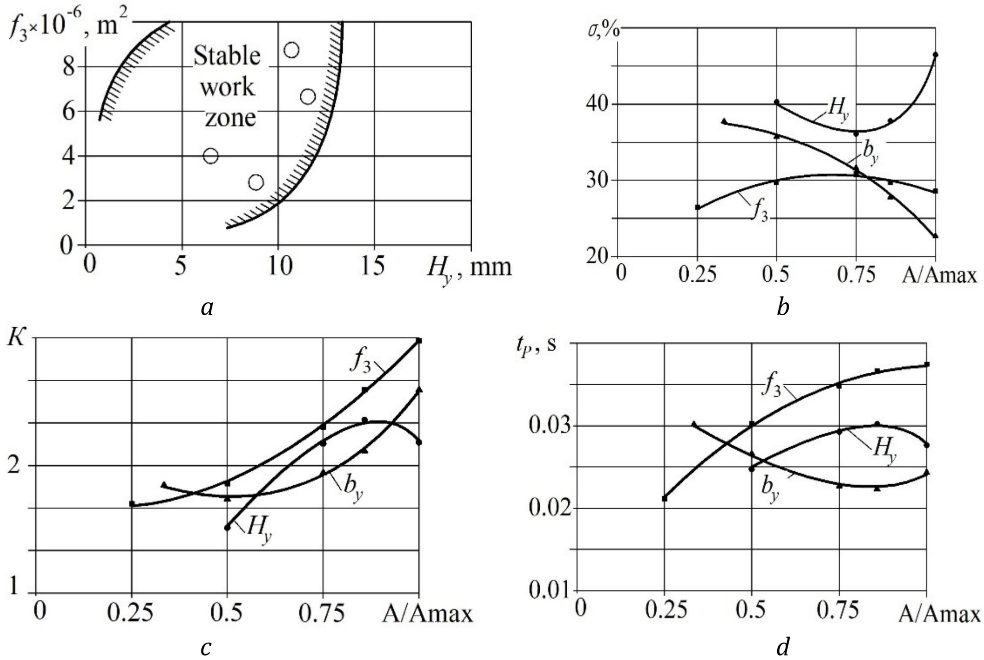

Figure 7: Influence of the initial spring compression H_y, throttle opening area f_3, and viscous damping coefficient of the valve elements b_y on the dynamic characteristics: a - influence on stability; b - influence on overshoot; c - influence on oscillation index; d - influence on settling time. The circles indicate experimentally obtained points

The research results made it possible to determine the stable operating region of the proposed hydraulic drive with independent metering. It was established that the admissible ranges of the design parameters of the pilot-operated check valves are interrelated, and their influence on dynamic characteristics is interdependent and cannot be assessed separately.

Changing the initial compression of the pilot-operated check-valve spring substantially affects the overshoot and oscillation index of transient processes, whereas the opening area of the throttle elements mainly determines the response speed of the hydraulic drive. Increasing the viscous damping coefficient of the valve elements helps reduce overshoot and settling time; however, it may increase the oscillatory behavior of the system.

The obtained dependencies make it possible to formulate practical recommendations for selecting the design parameters of pilot-operated check valves that ensure stable hydraulic-drive operation and the required dynamic characteristics in transient modes.

6. Discussion and Recommendations

This paper proposes a structural solution for the hydraulic drive of loading and unloading machines based on functional separation between the elements controlling working-fluid flows and the elements ensuring sealing of the working chambers. In contrast to traditional independent metering systems [13], the proposed approach uses fewer elements, each performing a separate function. This simplifies the hydraulic-drive design and increases its flexibility.

Solving the mathematical model produced transient processes in the hydraulic drive, which make it possible to evaluate the operating quality of its components. Dependencies were obtained that determine the influence of pilot-operated check-valve design parameters on operating stability (Fig. 7, a) and on the dynamic characteristics (Fig. 7, b-d) of the hydraulic drive.

The analysis showed that increasing the initial compression H_y of the pilot-operated check-valve springs increases overshoot, whereas its minimum values are achieved in the middle range of this parameter (Fig. 7, b). At the same time, this range is accompanied by an increase in the oscillation index and settling time, which indicates the non-uniform influence of this parameter.

Using throttles with the smallest opening area f_3 reduces the settling time t_p (Fig. 7, d), improves the response speed of the hydraulic-drive elements, reduces the oscillation index K (Fig. 7, c), and decreases overshoot to σ = 26% (Fig. 7, b). At the same time, excessive reduction of this parameter narrows the stable operating region of the system (Fig. 7, a), which must be considered during hydraulic-equipment design.

Increasing the viscous damping coefficient of the valve elements by reduces overshoot and shortens the transient time t_p (Fig. 7, b, d); however, it may worsen the oscillatory properties of the hydraulic drive (Fig. 7, c).

The obtained results confirm that the influence of pilot-operated check-valve design parameters on the dynamic characteristics of the hydraulic drive is interrelated and cannot be considered in isolation.

The studies performed using the mathematical model are limited and focus on determining the influence of the design parameters of pilot-operated check valves; they do not fully cover the parameters of all hydraulic-drive elements. The paper also presents experimental results that confirm the transient processes obtained using the mathematical model and the adopted assumptions.

Future studies will improve and extend the mathematical model to account for the influence of the design parameters of other elements. Further research will also consider specific operating modes of the hydraulic drive for particular machine equipment.

The recommended ranges of H_y, f_3, and b_y are directly applicable to the investigated hydraulic-drive configuration, actuator size, load conditions, and working-fluid properties. For other cylinder dimensions, load magnitudes or directions, fluid temperatures, duty cycles, and machine operating conditions, the quantitative ranges should be recalculated or experimentally verified. The obtained trends remain useful for similar independent-metering hydraulic drives in which pilot-operated check valves determine the transient response.

7. Conclusions

A structural circuit of a hydraulic drive for loading and unloading machines with independent metering of working-fluid flows is proposed. It is based on functional separation between flow-control elements and elements that ensure sealing of the working chambers. The use of several independent proportional directional-control elements in combination with pilot-operated check valves creates conditions for energy-saving operating modes, including motion of the working member using accumulated load energy, without structural complication of the hydraulic drive.

A mathematical model was developed to study the proposed hydraulic drive. The model accounts for the interaction between proportional directional-control elements and pilot-operated check valves under independent metering modes. Solving the model made it possible to obtain transient processes and analyze the influence of hydraulic-equipment design parameters on the dynamic characteristics of the hydraulic drive in different operating modes.

Numerical simulation established the regularities by which the initial compression H_y of the pilot-operated check-valve springs, the opening area f_3 of the throttle elements, and the viscous damping coefficient b_y of the valve elements influence hydraulic-drive stability, overshoot, oscillation index, and transient time. The obtained dependencies are characterized by trade-offs and allow the design parameters to be selected in a justified manner to achieve the required dynamic characteristics.

Practical recommendations were formulated for selecting the main design parameters of pilot-operated check valves: the initial compression H_y of the valve springs, the opening area f_3 of the throttle working windows, and the viscous damping coefficient b_y of the valve elements. These parameters ensure stable operation of the hydraulic drive with independent metering and the required response speed in transient modes.

Preliminary experimental studies of transient processes are in qualitative agreement with the mathematical-simulation results, confirming the adequacy of the proposed structural circuit and the developed mathematical model.

References

[1] Vukovic, M., Leifeld, R., Murrenhoff, H. (2017) Reducing Fuel Consumption in Hydraulic Excavators—A Comprehensive Analysis. Energies, 10, 687 https://doi.org/10.3390/en10050687

[2] Shen, C., Zhu, J., Chen, J., Li, S., Yi, L. (2025). Parameter matching and optimization of hybrid excavator swing system. Journal of Zhejiang University-SCIENCE A, 26(2), 138-150. https://doi.org/10.1631/jzus.A2400040

[3] Bereziuk, O., Petrov, O., Lemeshev, M., Slabkyi, A., Sukhorukov, S. (2023). Transient processes quality indicators of the rotation lever hydraulic drive for the dust-cart manipulator. In Design, Simulation, Manufacturing: The Innovation Exchange. Cham: Springer Nature Switzerland. pp. 3-12 https://doi.org/10.1007/978-3-031-32774-2_1

[4] Lozinskyi, D. O., Petrov, O. V., Semichasnova, N. S., Gromaszek, K., Kalimoldayev, M.,

Borankulova, G. (2021). Application of feedback elements in proportional electrohydraulic directional control valve with independent flows control. In Mechatronic Systems 1. pp. 127-136. Routledge. https://doi.org/10.1201/9781003224136-11

[5] Axin, M., Eriksson, B., Krus, P. (2016). A flexible working hydraulic system for mobile machines. International journal of fluid power, 17(2), 79-89. https://doi.org/10.1080/14399776.2016.1141635

[6] Padovani, D., Rundo, M., Altare, G. (2020). The Working Hydraulics of Valve-Controlled Mobile Machines: Classification and Review. ASME. J. Dyn. Sys., Meas., Control. 142(7): 070801. https://doi.org/10.1115/1.4046334

[7] Padovani, D., Ketelsen, S., Hagen, D. Schmidt, L. (2019). A Self-Contained Electro-Hydraulic Cylinder with Passive Load-Holding Capability. Energies,12(2). https://doi.org/10.3390/en12020292

[8] Patent CN107676316A, F15B 11/08, F15B 13/04, F16D 48/06. A kind of braking control system and control method applied to hydraulic open system / Gao Yingjie, Zhu Shiqi, Yu Kai, Zhai Chang, Cui Pengbo, Chang Feixiang; Yanshan University. 11.07.2017. 10 p. https://patents.google.com/patent/CN107676316A/en

[9] Thanh Ha Nguyen , Tri Cuong Do, Kyoung Kwan Ahn (2020) Independent Metering Valve: A Review of Advances in Hydraulic Machinery / Journal of Drive and Control, Vol.17 No.4 pp.54-71. https://doi.org/10.7839/ksfc.2020.17.4.054

[10] Ding, R., Sun, G., Zhang, J., Peng, L., Cheng, M., Xu, B., Yang, H. (2025). A review of independent metering control system for mobile machinery. International Journal of Hydromechatronics, 8(5), pp. 1-39. https://doi.org/10.1504/IJHM.2025.10069815

[11] Xiaogang Zhang, Shufei Qiao, Long Quan, Lei Ge (2019) Velocity and Position Hybrid Control for Excavator Boom Based on Independent MeteringSystem. IEEE Access 2019,7, 71999–72011. https://doi.org/10.1109/ACCESS.2019.2919953

[12] Nguyen, T.-H.; Do, T.-C.; Ahn, K.-K. (2022) A Study on a New Independent Metering Valve for Hydraulic Boom Excavator. Appl. Sci. 2022, 12, 605. https://doi.org/10.3390/app12020605

[13] Nguyen, T. H., Do, T. C., Phan, V. D., Ahn, K. K. (2023). Working performance improvement of a novel independent metering valve system by using a neural network-fractional order-proportional-integral-derivative controller. Mathematics, 11(23), 4819. https://doi.org/10.3390/math11234819

[14] Polishchuk, L., Piontkevych, O., Svietlov, A., Adler, O., Lozinskyi, D. (2025). Development and optimization of the control device for the hydraulic drive of the belt conveyor. Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Srodowiska. Vol. 15. No. 2.: 124–129. https://doi.org/10.35784/iapgos.7051

[15] Kozlov, L., Polishchuk, L., Piontkevych, O., Purdyk, V., Petrov, O. V., Tverdomed, V. M., Tungatarova, A. (2021). Optimization of design parameters of a counterbalance valve for a hydraulic drive invariant to reversal loads. In Mechatronic Systems 1. Routledge. pp. 137-148. https://doi.org/10.1201/9781003224136-12

[16] Mora-Melia, D., Gutiérrez-Bahamondes, J. H., Iglesias-Rey, P. L., Martinez-Solano, F. J. (2024). Exploring the synergy of problem-based learning and computational fluid dynamics in university fluid mechanics instruction. Computer Applications in Engineering Education, 32(6), e22782. https://doi.org/10.1002/cae.22782

[17] Petrov, O., Kozlov, L., Lozinskiy, D., Piontkevych, O. (2019). Improvement of the hydraulic units design based on CFD modeling. In Design, Simulation, Manufacturing: The Innovation Exchange. Cham: Springer International Publishing. pp. 653-660 https://doi.org/10.1007/978-3-030-22365-6_65

[18] Chen, Y., Wang, A., Li, X. (2023). Throttling characteristics prediction methodology for combined grooves in directional spool valves under variable flow rates. Heliyon, 9(10). https://doi.org/10.1016/j.heliyon.2023.e21029

[19] Bereziuk O.V., Lemeshev M.S., Bogachuk V.V., Kisala P., Tungatarova A., Yeraliyeva B. (2021) High-precision ultrasonic method for determining the distance between garbage truck and waste bin // Mechatronic Systems 1: Applications in Transport, Logistics, Diagnostics, and Control: collective monograph. London: Routledge. pp. 279-290. https://doi.org/10.1201/9781003224136-24

[20] Gubarev, A., Murashchenko, A., Yakhno, O., Tyzhnov, A., Gromaszek, K., Kalizhanova, A., Mamyrbaev, O. (2021) Calculations of unsteady processes in channels of a hydraulic drive. In: Mechatronic Systems 1, Routledge. pp. 149–160. https://doi.org/10.1201/9781003224136-13

[21] Kozlov, L. G., Polishchuk, L. K., Piontkevych, O. V., Korinenko, M. P., Horbatiuk, R. M., Komada, P., Orazalieva, S., Ussatova, O. (2019). Experimental research characteristics of counterbalance valve for hydraulic drive control system of mobile machine. Przeglad Elektrotechniczny, 95(4), 104-109. https://doi.org/10.15199/48.2019.04.18.