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Original Research Article

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ENHANCEMENT OF DYNAMICS AND DEVELOPMENT OF CONTROL METHODS FOR IMPULSE HYDRAULIC SHOCK MECHANISMS

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Abstract. *This study examines the dynamic characteristics and improvement of control methods for impulse hydraulic shock mechanisms used in high-performance hydraulic systems. The work focuses on eliminating the common discrepancy between theoretical and actual output parameters caused by inefficient processing of control signals. A mathematical model has been developed that describes the displacement, velocity, and acceleration of the actuator, taking into account nonlinear fluid dynamics and changes in external load. Based on this model, improved control methods are proposed, aimed at increasing system stability, reducing response errors, and improving the energy efficiency of the impact action. Numerical simulation has shown that adaptive input signal shaping significantly improves the system's performance. Under identical modeling conditions, the proposed logic-based control method reduced the normalized force deviation by approximately 15–20% compared with the conventional control scheme. A logical structure for generating the input signal X(t) has been developed, ensuring more precise synchronization of dynamic processes. The results obtained contribute to the development of control methods for hydraulic shock mechanisms and propose improved algorithms applicable in engineering systems where high accuracy and reliability are required. Future plans include experimental verification of the proposed solutions on physical prototypes, as well as refinement of the mathematical models to account for the compressibility of the working fluid and real-time load changes.*

Keywords: Impulse hydraulic shock mechanisms; mining machinery; control systems; actuator dynamics; mathematical modeling; input signal generation; logic circuits; numerical simulation; energy efficiency

1. Introduction

Hydraulic impact systems are used in mining equipment where short-time high-energy pulses are required for breaking, excavation, and related technological operations. Although such systems are well known in engineering practice, their actual operating parameters do not always coincide with the values predicted at the design stage. One of the reasons for this mismatch is the limited accuracy of control actions during different phases of the operating cycle, especially when the motion of the striker changes under load [1-3]. The performance of an impulse hydraulic mechanism depends not only on the hydraulic circuit itself, but also on how accurately the control signal is coordinated with the current kinematic state of the main actuating element. In cyclic operation, even small errors in signal formation may affect the displacement law, the stability of the return and working stroke phases, and the resulting impact characteristics. For this reason, the improvement of control methods remains an important task in the development of hydraulic shock systems [5-7].

A promising way to solve this problem is to construct the control action on the basis of motion parameters of the actuator. In this study, particular attention is paid to displacement, velocity, acceleration, and the third derivative of displacement as informative variables for control. Such an approach makes it possible to describe the dynamic state of the system more fully and to relate the generated signal to the actual motion of the striker during the full working cycle.

Based on the principles of control theory and mathematical logic, this paper develops logic schemes for signal formation in the return and working stroke phases of an impulse hydraulic shock mechanism. The proposed approach uses converters, integrators, and summing elements to decompose and transform the kinematic signals into the corresponding control action. The obtained schemes are intended to improve synchronization of dynamic processes and to reduce the discrepancy between calculated and actual operating parameters under practical conditions [7,8]. The purpose of the study is to improve the dynamic performance of impulse hydraulic shock mechanisms by developing control methods based on the kinematic parameters of the main actuating element. Special attention is given to the formation of logic-based control signals and to the use of acceleration and the third derivative of displacement as governing parameters for more accurate motion control.

The novelty of this study lies in the development of logic-based control methods for impulse hydraulic shock mechanisms in which the control action is formed from the kinematic parameters of the main actuating element, including displacement, velocity, acceleration, and the third derivative of displacement. Unlike our previous work, which focused on dynamic modeling and surface integrity optimization of low-frequency hydraulic impulse systems, the present study is aimed at improving the coordination of control signals.

2 Literature review and problem statement

Hydraulic shock and impulse systems have been studied for many years in connection with mining machines, hydraulic drives, and impact devices operating under cyclic loading. Earlier works mainly described the general theory of hydraulic impulse systems, the design principles of impact machines, and the motion laws of the main actuating element under different operating conditions. These studies created the theoretical basis for analyzing pressure changes, striker motion, and impact energy generation in hydraulic systems [9,10]. At the same time, practical operation of such systems shows that their efficiency depends not only on the hydraulic layout, but also on the quality of control during the full operating cycle. In real machines, deviations between calculated and actual output parameters often appear because the control signal is not sufficiently coordinated with the instantaneous dynamic state of the striker. This reduces motion accuracy, affects the stability of the return and working stroke phases, and may lead to a decrease in impact efficiency [11].

A number of researchers have considered continuous control methods for hydraulic systems, where the state of the main actuating element is monitored throughout the entire cycle. This approach is especially relevant for hydraulic machines operating at relatively low frequencies and under considerable force loading. Previous studies have also shown that the use of displacement, velocity, and acceleration as control-related variables can improve the precision of actuator motion. However, the use of the third derivative of displacement as a basis for forming the control action remains insufficiently developed for impulse hydraulic shock mechanisms. In oscillation theory, the third derivative of the motion law is known as sharpness and characterizes the rate of change of acceleration in time. From the viewpoint of control, this parameter is important because it reflects the dynamic intensity of the driving action and may provide a more sensitive basis for synchronizing the control signal with the actual motion of the striker. Although this concept has been mentioned in the literature on optimal hydraulic drive control, its application to logic-based signal formation in hydraulic shock systems has not yet been fully formalized.

Therefore, the main problem considered in this paper is the insufficient coordination between the control action and the actual motion of the main actuating element during the return and working stroke phases, particularly under resistance conditions. Conventional control approaches do not always ensure the required synchronization of dynamic processes, which leads to force deviation, reduced stability of the operating cycle, and lower agreement between design and real operating parameters [11,12]. The present study addresses this problem by developing logic-based methods for forming control signals from the kinematic parameters of the main actuating element, including displacement, velocity, acceleration, and the third derivative of displacement. In contrast to studies focused on surface integrity, machining effects, or digital monitoring, this work concentrates on improving the dynamic coordination of control actions during the full operating cycle of an impulse hydraulic shock mechanism [13].

3 Methodology

The methodological basis of this study combines elements of control theory, hydraulic drive analysis, and logic-based signal synthesis for cyclic impact systems. The research is aimed at improving the control of an impulse hydraulic shock mechanism by coordinating the generated control action with the kinematic state of the main actuating element during the full working cycle. Particular attention is given to the return and working stroke phases, since the dynamic behavior of the system in these intervals determines the accuracy of motion, the stability of the cycle, and the efficiency of impact energy transfer. At the first stage, the operating features of hydraulic shock systems used in mining machines were analyzed. These systems function under significant force loading and relatively low operating frequency, which makes continuous control methods more suitable than discrete approaches. Continuous control allows the state of the striker to be tracked throughout the whole cycle and makes it possible to influence the law of motion at any moment of time. On this basis, the study adopts the assumption that the change in control action can be described most completely through the higher-order kinematic characteristics of motion, including acceleration and the third derivative of displacement.

The next stage involved the construction of a mathematical description of the main actuating element motion. The model is based on the classical relation between the resultant force and acceleration and considers the motion of the striker along its axis. From this basis, analytical relations were used to describe the displacement, velocity, acceleration, and the variation of the control action in time. For simplification of the obtained expressions, dimensionless or reduced coefficients were introduced to reflect the connection between the input parameters of the hydraulic shock system and its output characteristics under given technical and operating conditions.

A separate part of the methodology concerns the formation of control signals for different motion phases. The return phase and the working stroke phase were considered separately, since the structure of the kinematic relations and the role of the control action differ in these two parts of the cycle. Based on the derived expressions, logic schemes were developed to generate the input signal and the corresponding control action. These schemes were built using converters, integrators, phase-shifting elements, multipliers, and summing units. Such a structure makes it possible to decompose the kinematic signal into components, transform them using the required coefficients, and combine them into the final control function. Special attention was paid to the use of acceleration and the third derivative of displacement as governing parameters. In the adopted approach, the third derivative characterizes the rate of change of acceleration and is treated as an informative quantity for continuous control of the striker motion. This makes it possible to form a control signal that is more sensitive to transient changes in the operating state of the mechanism and to improve synchronization between the hydraulic and mechanical processes during the cycle.

The methodology also includes analysis of system behavior under constant resistance. In this case, the control action was formed with allowance for the drag-related terms affecting the striker motion. The comparison of signal structures under resistance and no-resistance conditions was used to reveal how the amplitudes and durations of control impulses change depending on the operating environment. This comparison provides the basis for evaluating the adaptability of the proposed control schemes and their suitability for practical hydraulic shock systems working under load. At the final stage, the developed logic schemes and analytical relations were used for numerical analysis of the control process. The purpose of this stage was to assess the qualitative behavior of the generated control actions, to compare conventional and improved signal formation principles, and to identify the control variables that provide the most accurate coordination of dynamic processes. The methodology therefore combines analytical derivation, phase-based signal synthesis, and comparative dynamic analysis, which together form the basis for improving the control of impulse hydraulic shock mechanisms.

4 Formation of control signals

The formation of control actions in the impulse hydraulic shock mechanism is based on the kinematic parameters of the main actuating element during the full operating cycle. In the adopted approach, displacement, velocity, acceleration, and the third derivative of displacement are treated as informative variables that reflect the current dynamic state of the striker. The purpose of the control scheme is to transform these variables into a coordinated control action that ensures stable motion in both the return phase and the working stroke phase.

From the control standpoint, the return phase and the working stroke phase must be considered separately. Although both phases belong to the same cycle, the structure of motion and the role of the control action are different in each of them. For this reason, the signal formation process was developed not as a single universal transformation, but as a phase-dependent logic procedure that takes into account the specific form of the kinematic relations in each interval.

At the analytical level, the control action is related to the law of motion of the main actuating element and to its derivatives. The starting point of the signal synthesis is the set of kinematic expressions describing the striker motion. In order to simplify their practical use, coefficients were introduced to connect the motion parameters with the operating and design conditions of the hydraulic shock system. These coefficients make it possible to adapt the control signal to a particular machine configuration and to the expected resistance conditions.

In the present study, the mathematical model is used to describe the phase-dependent motion of the main actuating element and to determine the corresponding control action. The return phase and the working stroke phase are considered separately because the direction of motion, the influence of resistance, and the required control signal differ in these two parts of the operating cycle. Therefore, the analytical expressions are written in a reduced form using coefficients that combine the design and operating parameters of the hydraulic shock system.

As a working hypothesis, the assumption that the third time derivative of its law of motion characterizes the change of the control action on the main actuating element in time to the fullest extent is used. Indeed, if we have in mind the classical expression

$$m\bar{a} = \bar{F} \ ,$$

where m – reduced mass of the main actuating element; $\bar{\boldsymbol{F}}$ - the resultant of all forces acting on it; $\bar{\boldsymbol{a}} = \ddot{\boldsymbol{x}}$ - acceleration; $\boldsymbol{x}(\boldsymbol{t})$ - law of motion, then after some transformations we obtain:

$$\ddot{x}(t) = \frac{1}{m}\bar{F} \ .$$

If we take into account that the motion of the main actuating element is carried out along its axis, then

$$\ddot{x}(t) = \frac{1}{m}F \ ; \ \dddot{x}(t) = \frac{1}{m}\frac{dF}{dt} = \frac{1}{m}U(t),$$

where $U(t)$ – change in control action.

It should also be noted that the classical literature devoted to the theory of oscillations [8] uses the third time derivative of the law of motion, which is called sharpness. In physical terms, it is the intensity of change of acceleration in time. Practical realization of sharpness in control theory has found application in the study of the speed-optimal hydraulic drive, in particular, in [9]. Here it is convincingly proved, this approach allows "to provide the movement of the actuator actuator with minimum deviations from the required". Thus, sharpness is accepted as a setting influence for continuous methods of forming the control action [8]. The adopted method of forming the control action determines the stages of creating the automatic control body of the hydraulic shock system, different from the previously mentioned. The difference lies in the fact that before the structural synthesis of the control body, the establishment of the law of motion of the main actuating element of the system is made on the basis of operational requirements and limitations imposed on the system as a whole, as well as assumptions adopted in the study of the motion of the main actuating element. The found law of motion is a starting point for establishing the law of change of the control action in analytical form using the third time derivative.

The construction of the control action for this case is based on the laws of motion of the main actuating element obtained in Section 2.3. To simplify the equations defining the kinematic parameters of the main actuating element, we introduce coefficients expressing the relationship between the parameters and output parameters of the hydraulic shock system:

$$A^{(c)} = \frac{lp\left[1-(k_P-k_c)\varepsilon\right]}{(\varepsilon-1)}; \ B^{(c)} = \frac{lp(\varepsilon+1)}{(\varepsilon-1)}\left(\alpha-\frac{C_o}{1+C_o}\right)\times\sqrt{\frac{(\varepsilon-1)(1+\mu_{uc})\left[U(\varepsilon+1)-1\right]}{(1+C_o)\left[1+\varepsilon(1-2k_c)\right]}};$$

$$C^{(c)} = \frac{\left[(k_p-k_c)\varepsilon+1\right]}{(1+C_o)(\varepsilon-1)}; \ E^{(c)} = \frac{lp(1-k_c)}{(\varepsilon-1)}.$$

If necessary, these coefficients can be expressed through the input design and operating parameters of the hydraulic shock system.

Taking into account the introduced coefficients, the kinematic indices of the main actuating element of the system have dependencies:

in the reverse phase:

$$X = A^{(c)}\cos k_2 t + B^{(c)}\sin k_2 t + (C^{(c)} + D^{(0)}t); \tag{4.1}$$

$$\dot{X} = -A^{(c)}k_2 \sin k_2 t + B^{(c)}k_2 \cos k_2 t + D^{(0)}; \tag{4.2}$$

$$\ddot{X} = -A^{(c)}k_2^2 \cos k_2 t - B^{(c)}k_2^2 \sin k_2 t; \tag{4.3}$$

$$\dddot{X} = A^{(c)}k_2^3 \sin k_2 t - B^{(c)}k_2^3 \cos k_2 t; \tag{4.4}$$

in the travel phase:

$$X_1 = E^{(c)}(1 - \cos k_3 t); \tag{4.5}$$

$$\dot{X}_1 = E^{(c)}k_3 \sin k_3 t; \tag{4.6}$$

$$\ddot{X}_1 = E^{(c)}k_3^2 \cos k_3 t; \tag{4.7}$$

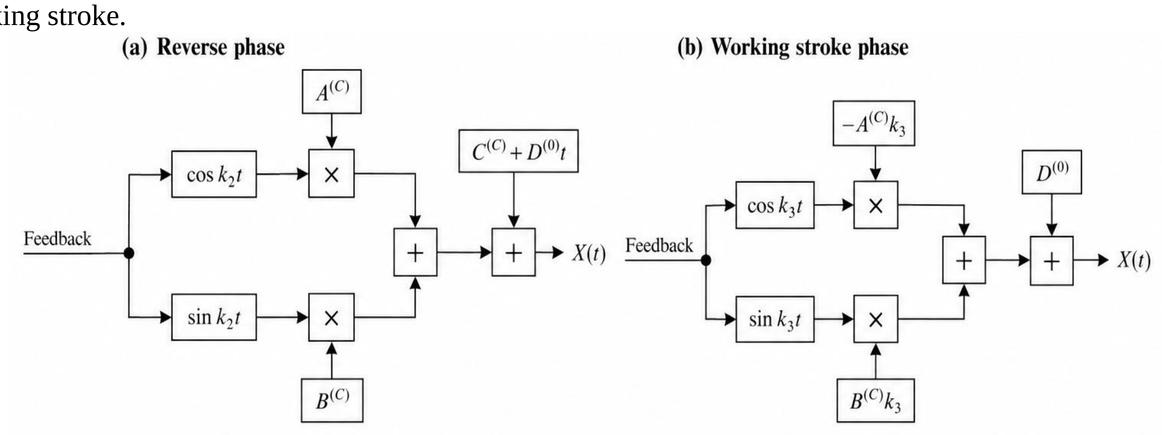
$$\dddot{X}_1 = -E^{(c)}k_3^3 \sin k_3 t. \tag{4.8}$$

In Equations (4.1)–(4.8), the motion of the main actuating element is described through displacement, velocity, acceleration, and the third derivative of displacement. The displacement characterizes the position of the striker along its working axis, the velocity describes the rate of this displacement, and the acceleration reflects the intensity of force interaction during the return and working stroke phases. The third derivative of displacement, referred to in this study as sharpness, characterizes the rate of change of acceleration over time and is used as an informative parameter for forming the control action.

The reduced coefficients used in these equations are introduced to simplify the analytical representation of the motion law. They combine the influence of the reduced mass of the actuating element, the parameters of the hydraulic drive, the phase of motion, and the resistance conditions. These coefficients are not independent empirical variables; they are used to present the return and working stroke equations in a compact form and to relate the mathematical model to the physical operating conditions of the hydraulic shock mechanism.

In terms of construction, the obtained expressions are similar to the dependences obtained in the study of the mode without resistance. As a consequence, the order of formation of signals determining the kinematic parameters of the main actuating element remains similar to that considered earlier [14,15].

The logic diagrams in Figures 1–6 show the sequence of signal-conditioning operations used to obtain the control action. In these diagrams, the input kinematic functions are decomposed into separate components. Each component is then transformed by multiplication with the corresponding coefficient, and the transformed components are combined in summing units. Multipliers represent coefficient-based scaling operations, while summing blocks represent the formation of the final control signal from several transformed components. Phase-shifting elements are used when the control signal requires temporal or phase correction during the working stroke.

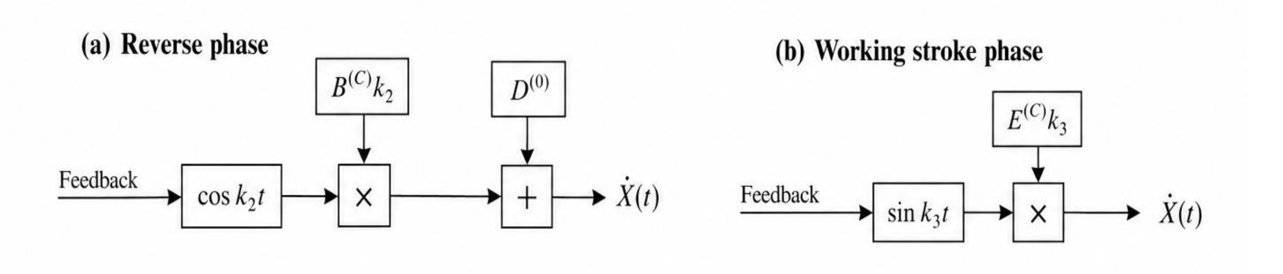


a and *b* - in reverse and working stroke phases, respectively

Fig. 1. Logical diagram of X(t) signal formation

The signal formation procedure is illustrated by the circuit shown in Figure 1. During the return phase, the input kinematic functions are generated and then multiplied by the corresponding coefficients. The transformed components are combined with the constant term to form the required signal for this phase.

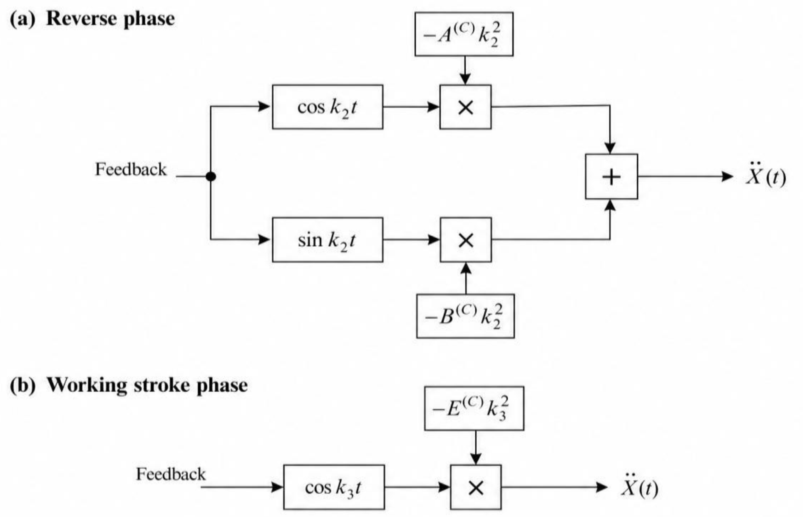
During the working stroke phase, the generated signal component is multiplied by the corresponding coefficient to obtain the control signal for the forward motion. This procedure provides a phase-dependent transformation of the input signal and makes it possible to adapt the control action to the operating conditions of the hydraulic shock mechanism [14].



a and *b* - in reverse and working stroke phases, respectively

Fig. 2. Sequence of signal conditioning operations

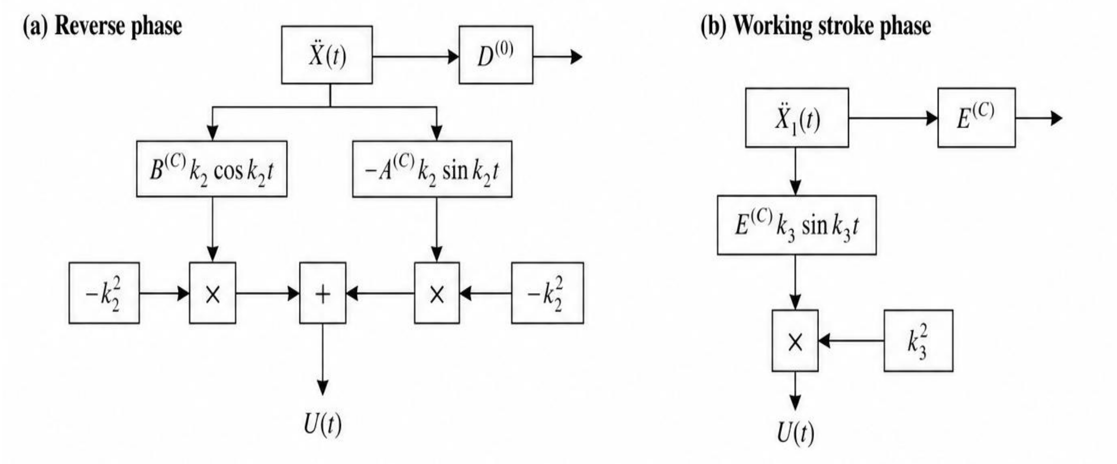
In the backward phase (Figure 2a), the generated functions f_1 and f_2 are simultaneously multiplied by the corresponding coefficients k_1 and k_2. The resulting transformed signals are then summed together. In the working stroke phase (Figure 2b), the function generated in this mode must be multiplied by the coefficient k_3. This is the easiest way to generate a signal $\ddot{X}(t)$. Comparison of expressions determining the change of kinematic parameters of motion of the main actuating element during the working cycle makes it possible to construct a control action *U(t).*



a and *b* - in reverse and working stroke phases, respectively

Fig. 3. Logic circuit of signal formation

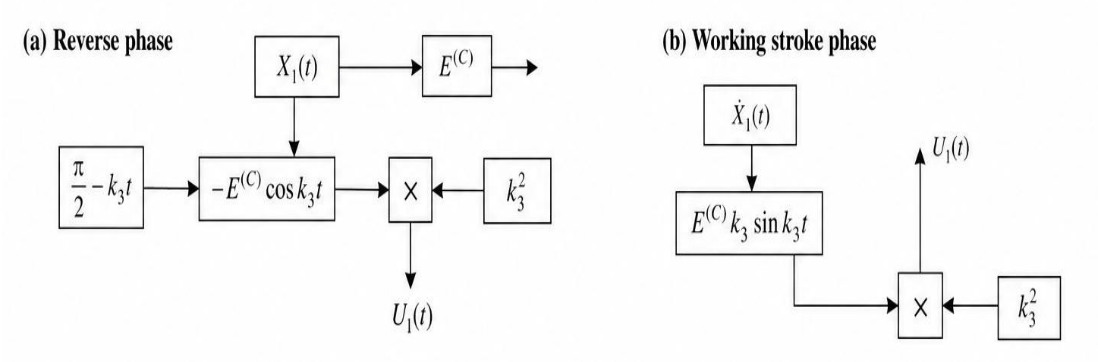
The logic scheme for forming the control action using the displacement signal $X(t)$is shown in Figure 3. During the return phase, the displacement signal is decomposed into several components. The required components are multiplied by the corresponding coefficients and then summed to obtain the control action $U(t)$. The remaining component obtained after signal decomposition does not contribute to the resulting control function in this phase. During the working stroke phase, the corresponding signal component is transformed by phase correction and coefficient scaling. This makes it possible to obtain a control function that corresponds to the required motion phase [15-17].



a and *b* - in reverse and working stroke phases, respectively
Fig. 4. Logic scheme of control action formation U(t) Displacement

Constructing the control action using the velocity v(t) and functions f_i is performed in accordance with the logic diagram shown in Figure 4. In the reverse phase (Figure 4a), the signal v(t) is decomposed into the components f_1, f_2, and f_3. The last two components are simultaneously multiplied by the corresponding coefficients, after which the transformed signals are summed. The remaining component obtained after decomposition does not contribute to the formation of the resulting control function.

In the working stroke phase (Figure 4b), the component that fully defines the control signal is multiplied by its corresponding coefficient.



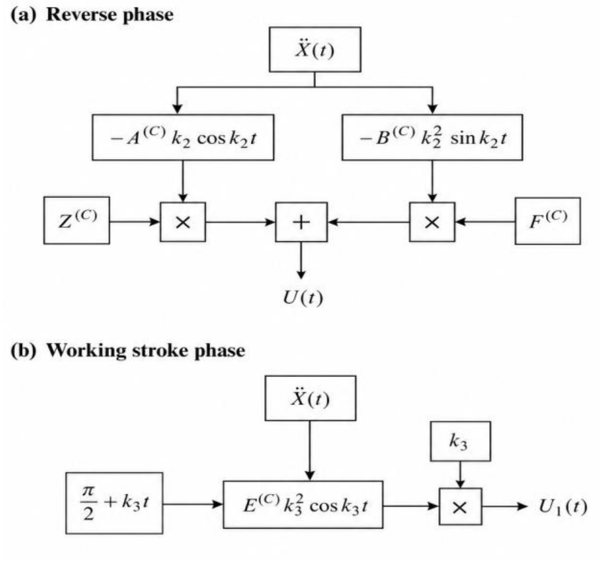
a and *b* - in reverse and working stroke phases, respectively
Fig. 5. Logic scheme of control action formation using the acceleration signal

The control action based on the acceleration signal is formed according to the logic scheme shown in Figure 5. During the return phase, the acceleration-related signal is decomposed into two components. These components are multiplied by the corresponding coefficients and then summed to form the resulting control action for this phase.

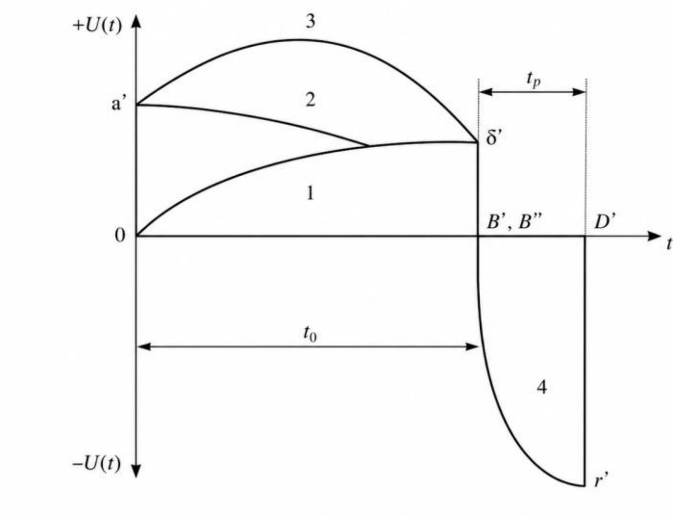
During the working stroke phase, the corresponding signal component is transformed by applying the required phase shift and coefficient scaling. This operation allows the control action to be synchronized with the dynamic state of the main actuating element.

Thus, under constant resistance conditions, the general logic of control signal formation remains similar to the no-resistance case. The main difference is quantitative: the coefficients applied to the signal components change because the control action must compensate for external resistance.

The variation of the control action for the considered case is determined by the expressions describing the motion of the main actuating element during the operating cycle. After transformation of these expressions in accordance with the developed logic schemes, the resulting control-action diagram for motion under constant resistance takes the form shown in Fig. 7. Its characteristic points are o, a', b', c', d', and e'. The values of the control action at the beginning and at the end of the cycle phases are defined by the corresponding segments of the diagram.



a and *b* - in reverse and working stroke phases, respectively
Fig. 6. Logic scheme of control action formation U(t) using acceleration



1 - $A^{(C)}k_2^3\sin k_2 t$; 2 - $-B^{(C)}k_2^3\cos k_2 t$; 3 – U(t); 4 – U_1(t)
1 – kinematic parameter curve; 2 – auxiliary dynamic curve; 3 – U(t); 4 – U_1(t)
Fig. 7. Dynamic diagram of motion parameters and control actions of the hydro-impact system

In comparison with the no-resistance case, these segments become larger due to the influence of the drag force coefficient K_c and the related changes in the governing coefficients. Thus, the obtained diagram reflects the effect of resistance on the amplitude and duration of the control action during the operating cycle.

The coefficient K_c is used as a normalized resistance coefficient. It characterizes the influence of external resistance on the motion of the main actuating element. The case $K_c = 0$corresponds to motion without resistance, whereas $K_c > 0$corresponds to motion under resistance conditions. An increase in K_c changes the required control action and leads to longer and more intensive control impulses during the working stroke.

When K_c approaches to zero, the control-action diagram approaches the no-resistance case. This confirms that resistance mainly affects the amplitude and duration of the control action, while the general structure of the signal formation process remains unchanged.

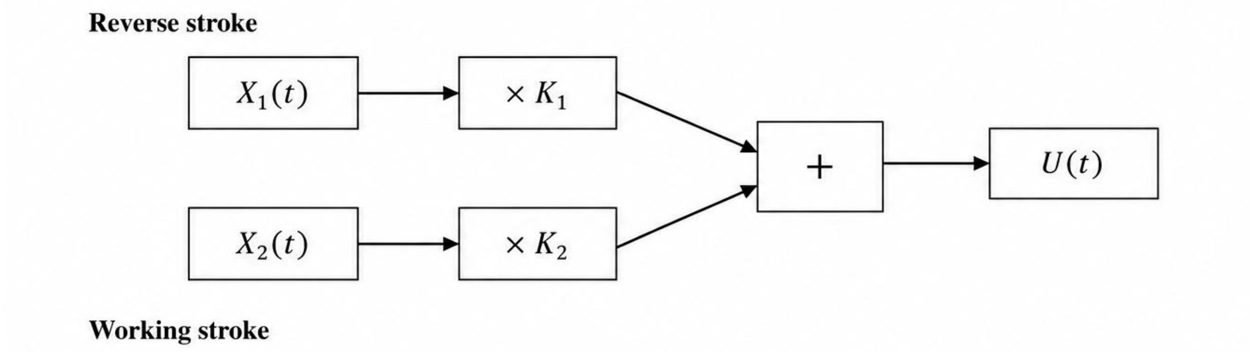


Fig. 8. Logical scheme of the signal formation process

The signal X(t) is generated by multiplying input functions $X_1(t)$ and $X_2(t)$ by constants K_1 and K_2, and summing the results to form the control action U(t).

Figures 8 and 9 summarize the auxiliary signal formation process. The input signals are scaled by the corresponding coefficients and then combined with the constant term to obtain the auxiliary control signal. This structure allows the control action to be adapted to the resistance conditions and to the selected phase of the operating cycle.

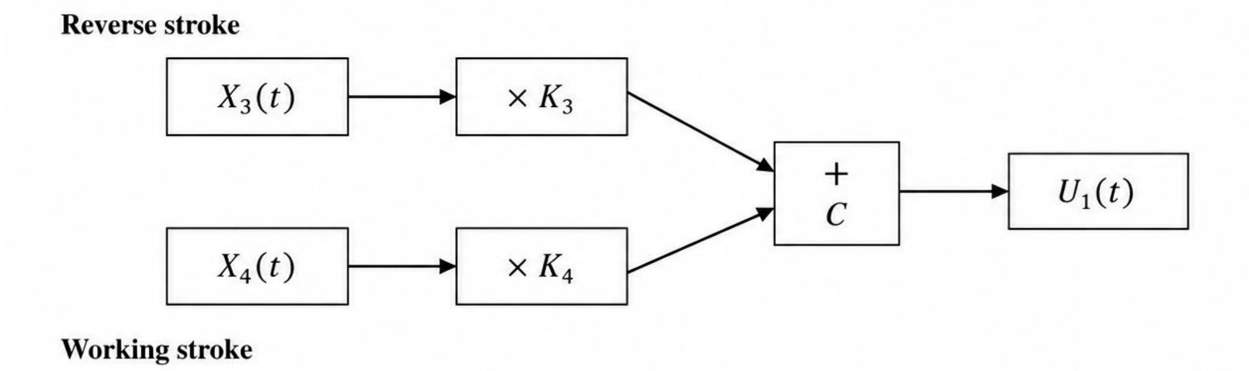


Fig. 9. Logic structure for generating the auxiliary control signal U1(t)

Input signals $X^3(t)$ and $X_4(t)$ are scaled by coefficients K_3 and K_4, then added with a constant C to generate the output control signal $U_1(t)$.

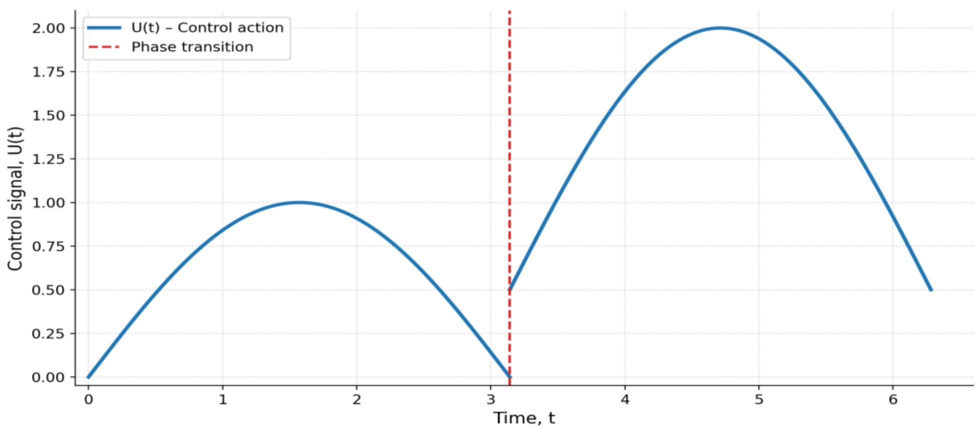


Fig. 10. Control action diagram under resistance conditions

The signal becomes more intense and prolonged during the working stroke to compensate for external resistance. This ensures accurate actuator motion and minimizes energy losses.

For each phase, the control signal U(t) is formed through a logic scheme consisting of:

– Signal decomposition: Splitting the motion law into components (e.g., $X_1(t)$, $X_2(t)$)

– Coefficient adjustment: Each component is multiplied by a system-specific constant based on design parameters and operating conditions

– Summation: Resulting signals are combined into a unified control function

To validate the proposed control strategy based on displacement, velocity, acceleration, and sharpness, a mathematical simulation of the actuator’s motion was carried out. The actuator's displacement is modeled as a sinusoidal function over time.

Mathematical Model

Displacement function:

$X(t) = A \cdot sin(\omega t)$, where $A = 0.1m$, $\omega = 2\pi f$, and $f = 2Hz$

First derivative (velocity):

$V(t) = A\omega \cdot cos(\omega t)$

Second derivative (acceleration):

$A(t) = -A\omega^2 \cdot sin(\omega t)$

Third derivative (sharpness):

$S(t) = -A\omega^3 \cdot cos(\omega t)$

In this simulation, the sinusoidal displacement law was used as a simplified test function for evaluating the behavior of the control variables. The purpose of this model is not to reproduce all nonlinear hydraulic effects experimentally, but to compare how different kinematic quantities change over time and how they can be used for control signal formation. Velocity, acceleration, and sharpness were obtained by differentiating the displacement function with respect to time.

Simulation Results

The figure below illustrates the time-dependent behavior of four key motion parameters: displacement $X(t)$, velocity $V(t)$, acceleration $A(t)$, and sharpness $S(t)$.

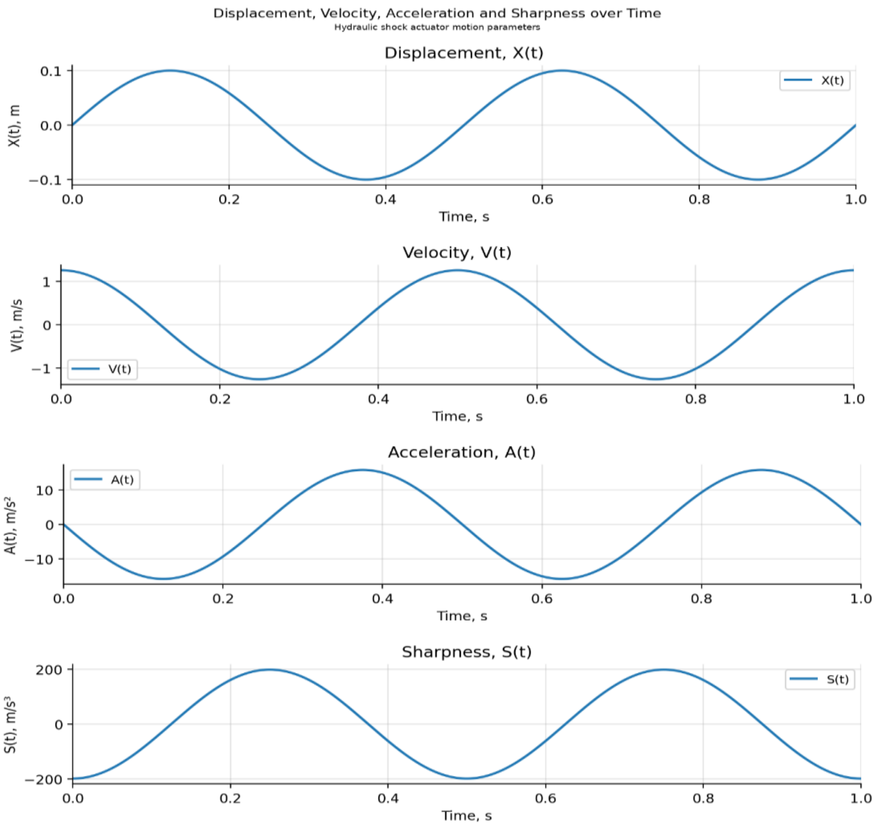


Fig. 11. The time-dependent behavior of four key motion parameters

The displacement follows a smooth sinusoidal profile. Velocity peaks at zero-crossings of displacement, while acceleration reaches maximum values at displacement extremes. Sharpness, being the third derivative, shows the most rapid oscillations and highlights the responsiveness of the actuator's dynamics. This confirms the suitability of using sharpness as a control input in hydraulic impact systems.

When resistance is present, additional terms are introduced to offset the drag force coefficient K_c. This leads to stronger and longer control impulses during the working phase. The influence of resistance is visualized in comparative signal diagrams, where segments of the control function are visibly altered.

5 Results and Discussion

The proposed control strategies for hydraulic impact mechanisms were evaluated by means of mathematical modeling and numerical simulation. The analysis was performed using the main kinematic parameters of the actuating element, including displacement, velocity, acceleration, and sharpness, in order to assess the efficiency and accuracy of the developed control schemes. The obtained results showed that control based on acceleration and the third derivative of displacement provides more accurate tracking of the prescribed motion law than conventional approaches. In particular, the striker motion follows the required trajectory more closely during transitions between the return and working stroke phases, while overshoot and delay are reduced.

The improved synchronization between the generated control impulses and the mechanical response of the system also leads to better energy utilization. Under resistance conditions, the sharpness-based control method adjusts the control action more precisely in accordance with the current dynamic state of the actuating element. As a result, unnecessary energy expenditure is reduced and the operating cycle becomes more stable. The developed logic schemes also demonstrate adaptability to changing operating conditions, including variations in resistance force and the dynamic characteristics of the working element. Owing to the modular structure of the control diagrams, the coefficients of the governing relations can be adjusted according to the required operating mode.

A comparison of conventional and proposed control methods is presented in Table 1. The results indicate that the logic-based control scheme provides improved phase coordination, lower force deviation, and higher stability under load.

The reported 15–20% reduction in force deviation should be interpreted as a simulation-based comparative estimate. It was obtained by comparing the normalized deviation amplitudes of the conventional and proposed control schemes under identical modeling conditions. The relative reduction was calculated as

$$\eta = \frac{\Delta F_{conv} - \Delta F_{prop}}{\Delta F_{conv}} \times 100\%,$$

where ΔF_{conv} is the normalized force deviation for the conventional control scheme and ΔF_{prop} is the normalized force deviation for the proposed logic-based control scheme. This value is not presented as a full-scale experimental result. Experimental validation of the proposed control scheme is considered as the next stage of the research.

Table 1. Comparative assessment of conventional and proposed control methods

Performance criterion	**Conventional control scheme**	**Proposed logic-based control scheme**	**Improvement achieved**
Phase coordination	Incomplete synchronization between return and working stroke phases	Improved synchronization based on kinematic signal formation	Better coordination of operating phases
Force deviation	Baseline normalized deviation, ΔF_{conv}	Reduced normalized deviation, ΔF_{prop}	Approximately 15–20% reduction based on numerical simulation
Stability of operating cycle	Sensitive to resistance effects	More stable under resistance conditions	Increased cycle stability under load
Motion tracking accuracy	Moderate correspondence with the prescribed motion law	Improved correspondence with the prescribed motion law	Higher tracking accuracy
Adaptation to resistance effects	Limited compensation of resistance	Resistance coefficient K_c included in signal formation	Better compensation of external resistance
Energy utilization	Higher control losses	Reduced unnecessary control action under load	Improved energy utilization

The most direct quantitative improvement is related to the normalized force deviation. Under the same simulation conditions, the proposed logic-based control scheme reduced the normalized deviation amplitude by approximately 15–20% compared with the conventional scheme. The remaining criteria in Table 1 are presented as comparative engineering indicators because the present work is based on numerical modeling and logic-based signal synthesis. These criteria describe the observed improvement in phase coordination, resistance adaptation, and motion tracking behavior during the simulated operating cycle.

As shown in Table 1, the proposed logic-based control scheme demonstrates clear advantages over the conventional approach. The improved method provides more accurate phase coordination, lower force deviation, and greater stability under resistance conditions. In addition, the use of acceleration and the third derivative of displacement as governing parameters improves motion tracking accuracy and enhances the overall energy efficiency of the hydraulic shock mechanism.

6 Conclusions

This study examined the dynamic behavior of impulse hydraulic shock mechanisms and proposed improved control methods based on the kinematic parameters of the main actuating element. Particular attention was given to the formation of control signals from displacement, velocity, acceleration, and the third derivative of displacement in order to improve coordination between the generated control action and the actual motion of the striker during the operating cycle.

The developed logic-based approach makes it possible to form phase-dependent control signals for the return and working stroke phases and to adapt the control action to resistance conditions. The numerical simulation results indicate that the proposed method can reduce the normalized force deviation by approximately 15–20% compared with the conventional control scheme under the same modeling conditions.

The study also demonstrated that acceleration and sharpness can be used as informative governing parameters for hydraulic shock control, since they reflect transient changes in the dynamic state of the actuating element more sensitively than displacement alone. This provides a more accurate basis for signal generation and improves the correspondence between calculated and actual operating parameters.

Thus, the proposed control methods and logic schemes can be considered as a useful basis for improving the accuracy, reliability, and energy efficiency of impulse hydraulic shock mechanisms used in engineering applications. Further research will be aimed at experimental validation of the proposed solutions and refinement of the mathematical model with allowance for fluid compressibility, valve dynamics, and variable real-time loading conditions.

Conflict of interest statement
The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement
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Statement on the use of Artificial Intelligence
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