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Research Article

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DYNAMIC MODELING AND SURFACE INTEGRITY OPTIMIZATION OF LOW-FREQUENCY HYDRAULIC IMPULSE SYSTEMS

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Abstract. *This study investigates the dynamic behavior and surface integrity optimization of low-frequency hydraulic impulse systems operating under cyclic loading conditions. Particular attention is paid to the performance of the hydraulic module rod, which is subjected to repeated dynamic impacts during system operation. The influence of surface roughness, residual stresses, and microhardness on vibration stability and durability of friction pairs is analyzed. A dynamic mathematical model describing pressure variation, piston motion, and energy transfer within the hydraulic impulse chamber is developed. The model is implemented in the MATLAB/Simulink simulation environment for numerical analysis of transient processes. Experimental studies were conducted on cylindrical rod-type specimens made of 30KhGSA alloy steel processed using rotary multi-blade turning technology. The experimental results demonstrate that optimization of machining parameters significantly improves surface quality and reduces vibration amplitude of the hydraulic impulse system. The proposed modeling approach enables prediction of system dynamic behavior and provides a basis for improving operational stability. The obtained results confirm that the integration of advanced machining technologies with digital modeling tools can increase the reliability and efficiency of hydraulic impulse systems used in industrial applications.*

Keywords: Hydraulic impulse system, mechanical processing, surface roughness, dynamic load, mathematical modeling, system stability.

1. Introduction

Hydraulic impulse systems operate by converting the impulse energy of a working fluid into mechanical work within an extremely short period of time [1]. This conversion process is governed by the fundamental equations of hydrodynamics, including the momentum conservation equations, Bernoulli’s law, and the equations of motion of an incompressible fluid. During operation, a sharp pressure gradient dp/dt is generated in the pulse chamber of the hydraulic system. The magnitude of this gradient *c* is determined by the inertial properties of the working fluid and the propagation velocity of the pressure wave

$$c = \sqrt{\frac{K}{\rho}}$$

where K is the bulk modulus of the fluid and ρ is its density.

According to [2], cyclic variable loads arising during hydraulic impacts lead to a complex stress state in the rod of the hydraulic vibration module. These stresses can be described using Hooke's law, Hertz contact theory, and σ–N fatigue diagrams. Repeated cyclic loading causes plastic deformation of the rod material, which significantly influences its durability and operational reliability.

The quality of machining, including surface roughness, microstructure of the surface layer, and residual stresses, plays an important role in the efficiency of energy transfer in hydraulic impulse systems. As shown in the work [3], rotational friction processing leads to the formation of local temperature fields described by Fourier's heat conduction equation. These thermal processes promote the formation of a strengthened surface layer with increased microhardness due to recrystallization phenomena.

In recent years, the development of hydraulic impulse systems has increasingly involved digital modeling approaches. The concept of a digital twin, introduced [4], and further developed in the work [5], links changes in dynamic system parameters with fundamental physical laws governing pressure, velocity, momentum, and temperature distributions in space and time. [6] proposed a mathematical model of a hydro-impulse mechanism based on the Navier–Stokes equations, taking into account viscosity effects, turbulence, and the rate of pressure change in the working chamber. In the [7], the elasticity of the chamber walls was considered, requiring the use of wave equations describing the interaction between solid bodies and fluids. Work [8] analyzed the dynamics of multi-mass impulse systems using Lagrange equations of the second kind, considering stability factors such as damping coefficients, stiffness parameters, and inertial characteristics of the system elements. [9] investigated optimization of hydraulic system parameters in construction machinery based on energy balance equations $W_p = p \cdot V$ and pressure loss relations losses $\Delta p = f(\lambda, L/D)$, where λ is the friction coefficient and L/D represents the geometric characteristics of the flow channel. These parameters significantly affect the amplitude and frequency of pressure pulses in hydraulic impulse systems. The physical mechanisms of surface strengthening during finishing operations are described in [10, 11]. Induction hardening is based on the interaction between high-frequency electromagnetic fields and the metal surface layer, where Foucault currents generate heat according to Joule–Lenz's law. Subsequent rapid cooling leads to martensitic transformations that improve the mechanical properties of the material.

Thermo-frictional processing methods investigated [12–14] were numerically modeled using the ANSYS Workbench software environment. These models describe the distribution of temperature fields, stresses, heat flows, and deformations using the Fourier–Kirchhoff heat conduction equations and the von Mises plasticity criterion. [15] demonstrated that the dynamic behavior of hydraulic impulse systems is determined by the laws of conservation of energy and momentum. In this context, the elastic properties of the working elements play an important role, influencing the natural frequency of the system ω according to the relation

$$\omega = \sqrt{\frac{k}{m}},$$

where k is the stiffness coefficient and m is the mass of interacting elements.

Despite the significant number of studies devoted to hydraulic impulse systems, several important aspects of their operation remain insufficiently explored. In particular, the relationship between the surface integrity of critical mechanical components and the dynamic stability of low-frequency hydraulic impulse mechanisms has not yet been fully clarified. Most existing studies focus either on hydrodynamic processes occurring in the working chamber or on the mechanical properties of individual structural elements. However, in real operating conditions these factors interact simultaneously and significantly influence the overall performance of the system. Surface quality parameters, including roughness, residual stresses, and microstructural changes formed during machining, may directly affect vibration behavior, friction conditions, and the efficiency of energy transfer within the hydraulic impulse chamber. Nevertheless, the combined influence of machining quality, dynamic loads, and hydraulic parameters on system stability has not been sufficiently investigated. At the same time, the rapid development of digital technologies creates new opportunities for advanced modeling and optimization of complex hydraulic systems. Modern simulation environments make it possible to analyze transient processes, predict system behavior under variable loads, and evaluate the influence of technological parameters on system performance.

Therefore, the objective of this research is to investigate the physical and mechanical factors affecting the operation of low-frequency hydraulic impulse systems and to develop a dynamic model for analyzing their operating parameters. Particular attention is paid to the influence of surface integrity and machining technologies on vibration stability and energy efficiency of hydraulic impulse mechanisms. The scientific substantiation of operating parameters for complex engineering systems is an important research problem in modern applied mechanics and instrumentation [16].

2. Methodology and experimental section

In order to investigate the dynamic behavior of the hydraulic impulse system and evaluate the influence of machining parameters on the operational stability of the mechanism, a combined experimental and numerical research methodology was applied. The methodological framework of the study includes experimental investigation of the surface integrity of the hydraulic module rod, development of a mathematical model describing the dynamic interaction of hydraulic and mechanical elements, and numerical simulation of transient processes in the working chamber. The experimental part of the research was aimed at determining the influence of machining parameters on surface roughness and mechanical properties of the processed components. At the same time, the mathematical model was developed to describe pressure variations, piston motion, and energy transfer processes occurring in the hydraulic impulse chamber during cyclic loading. Numerical simulations were performed to analyze the dynamic response of the system and to identify the optimal operating parameters ensuring stable operation of the hydraulic impulse mechanism.

Such an integrated methodological approach allows combining theoretical modeling with experimental validation, which significantly increases the reliability of the obtained results and provides a deeper understanding of the physical processes occurring in low-frequency hydraulic impulse systems.

2.1. Object and experimental equipment

The research was carried out on cylindrical *"rod-type"* specimens with a diameter of 60 mm and a length of 120 mm, made of alloy steel 30KhGSA, which provides high strength and heat resistance. Machining was performed using the multi-blade rotary turning method, which reduces the thermal load in the cutting zone and ensures uniform wear of the cutting edges [16]. The operating parameters were selected experimentally within the following ranges: $n = 600–900$ rpm, $S = 0.10–0.30$ mm/rev, $t = 0.50–1.00$ mm. The average surface roughness R_a is determined by the formula:

$$R_a = \frac{1}{L}\int_0^L |\,y(x)|dx,$$

where $y(x)$is the deviation of the surface profile from the mean line and L is the sampling length.

The obtained Ra values ranged from 0.63 to 1.25 μm, confirming the efficiency of rotary turning compared to classical longitudinal cutting [17-18]. To ensure reliability of the obtained experimental results, each measurement was repeated five times. The average values of the measured parameters were used for further analysis. Statistical processing of the experimental data was performed using standard deviation and confidence interval estimation methods.

2.2. Mathematical Model of the Hydraulic Impulse System

The system dynamics are described by a set of motion equations for the working piston, taking into account damping and the variable pressure in the chambers:

$$M\frac{d^2x}{dt^2} + C\frac{dx}{dt} + Kx = P_A(t) - P_B(t) - F_c,$$

where: M – equivalent mass of the moving elements; C – viscous damping coefficient; K – stiffness of the return spring; P_A(t), P_B(t) – pressures in the working and return chambers; F_c – friction and sealing losses. The chamber pressures are defined as:

$$P_A(t) = P_0 + \rho c\frac{dx}{dt}, P_B(t) = P_0 - \rho c\frac{dx}{dt},$$

where ρ is the fluid density and c is the speed of sound in the medium.

The energy of a single impact is given by:

$$E = \frac{1}{2}Mv^2,$$

where $v = \frac{dx}{dt}$ is the piston velocity at the moment of impact.

During optimization, the system aims to minimize the loss function:

$$J = min \int_0^T [(P_A - P_B)^2 + \alpha v^2]\, dt,$$

where α is a weighting coefficient representing energy losses.

2.3. Digital simulation

The model was implemented in MATLAB/Simulink and Python SciPy, using the fourth-order Runge–Kutta integration method to solve the system of differential equations numerically [19].

The boundary conditions were defined as:

$$x(0) = 0, v(0) = 0, P_A(0) = P_B(0) = P_0 = 10 \text{ MPa}.$$

Based on the results, dependencies of x(t), v(t), and P(t) were obtained, along with the dynamic force diagrams. Model verification was carried out by comparing the experimental vibration and pressure data with the calculated curves (see Fig. 3).

2.4. Parameter Optimization Algorithm

At the cognitive layer of the digital twin, a combination of Gradient Descent and Random Forest Regressor algorithms was applied to identify parameters that ensure minimum surface roughness under acceptable load conditions [19]. The optimization function was defined as:

$$\Phi = w_1 \frac{R_a}{R_{a,ref}} + w_2 \frac{P_{max}}{P_{ref}} + w_3 \frac{A_{vib}}{A_{ref}} \rightarrow min,$$

where w_1, w_2, w_3 are the weighting coefficients for quality criteria; R_a is the surface roughness; P_{max} is the maximum pressure; and A_{vib} is the vibration amplitude.

The minimum of the objective function was reached at: $n = 860$ rpm, $S = 0.21$ mm/rev, $t = 0.70$ mm. Under these conditions, a balance is achieved between surface quality and hydraulic pulse stability.

2.5. Hardware–software Implementation

To synchronize the physical object with the virtual model, the MQTT protocol was employed, enabling real-time data exchange between sensors (pressure, temperature, vibration) and the simulation system. The data flow was visualized using the Node-RED Dashboard, while the computational results were automatically updated in MATLAB Live Script [20-21].

3 Results and discussion

The obtained results indicate that the dynamic stability of the hydraulic impulse system is significantly influenced not only by hydraulic parameters but also by the quality of mechanical processing of the working elements. In particular, the surface condition of the rod plays an important role in the formation of friction forces and vibration behavior of the system during cyclic loading. Improved surface integrity contributes to a more uniform distribution of stresses and reduces the probability of local stress concentration zones.

The experimental data confirm that optimization of machining parameters leads to a noticeable improvement in the operational characteristics of the hydraulic impulse mechanism. When the optimal cutting conditions were applied, the surface roughness decreased, which resulted in a reduction of friction losses and more stable piston motion in the hydraulic chamber. As a consequence, the energy transfer efficiency between the hydraulic and mechanical subsystems increased. The numerical simulation results also demonstrate that the proposed mathematical model adequately describes the transient processes occurring in the hydraulic impulse chamber. The calculated pressure fluctuations and piston displacement curves show good agreement with experimental observations. This confirms the applicability of the developed model for analyzing the dynamic behavior of similar hydraulic systems operating under cyclic impulse loading conditions.

In addition, the application of digital modeling tools makes it possible to analyze the influence of technological and operational parameters at the design stage of hydraulic equipment. This approach significantly reduces the need for expensive experimental testing and allows engineers to evaluate different operating scenarios before implementing the system in real industrial conditions. The research results confirmed the effectiveness of integrating a digital twin with a physical hydraulic pulse module. During the work, a three-level system structure was built (see Fig. 1), combining mechanical, hydraulic, and cognitive levels.

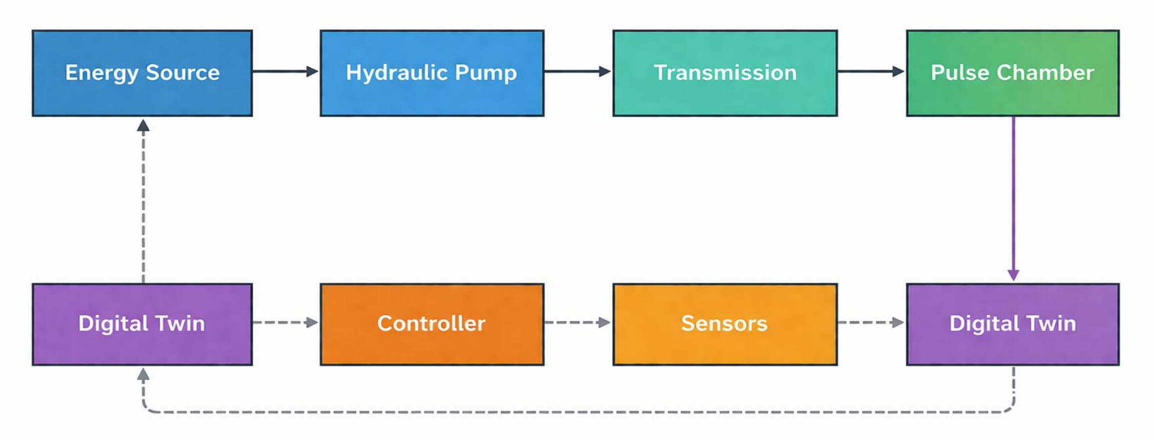

Fig. 1. Architecture of a hydraulic pulse module with a digital twin system (energy source – hydraulic pump – transmission – pulse chamber – sensors – controller – digital twin)

In the experimental part, the optimal parameters for rotary turning of the rod were determined (speed n = 870 rpm, feed S = 0.23 mm/rev, depth t = 0.75 mm). The obtained data were processed and visualized as a three-dimensional dependence of roughness on cutting parameters (Fig. 2).

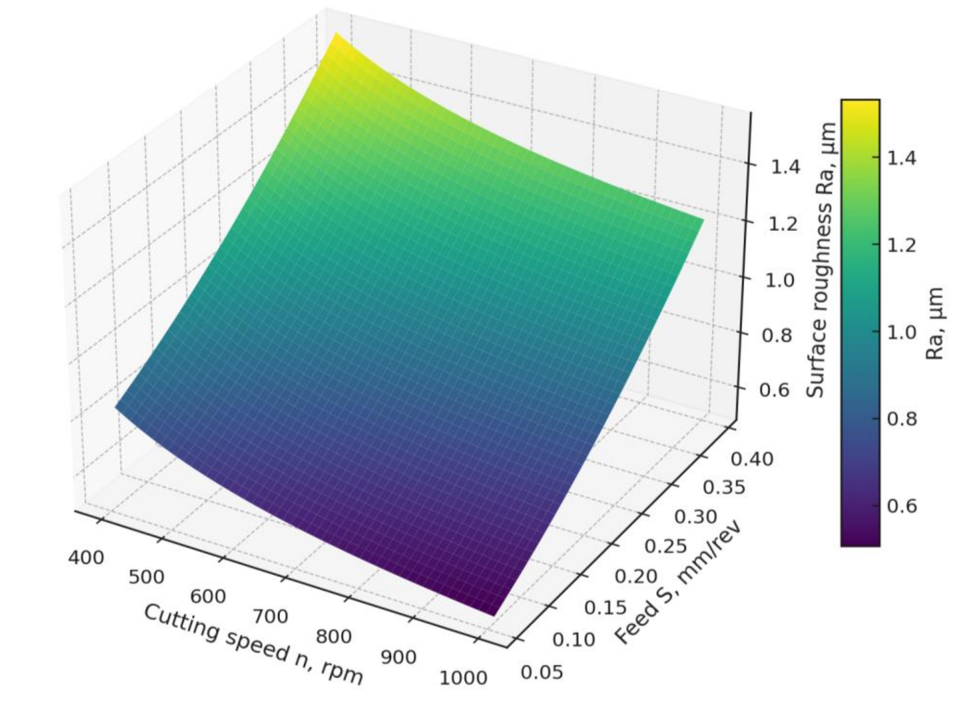

Fig. 2. Dependence of surface roughness Ra on speed n and feed S (the 3D graph shows the minimum Ra values in the range of high speeds and low feeds)

Numerical modeling has shown that the use of digital control significantly reduces pressure fluctuations in the working chamber (Fig. 3). The classic system exhibits increased pulsation, whereas when using a digital twin, the fluctuations stabilize with rapid attenuation [22].

Analysis of vibration activity showed that optimization of parameters led to a reduction in vibration amplitude by approximately 22% (Fig. 4). This reduces dynamic loads and extends the service life of the equipment.

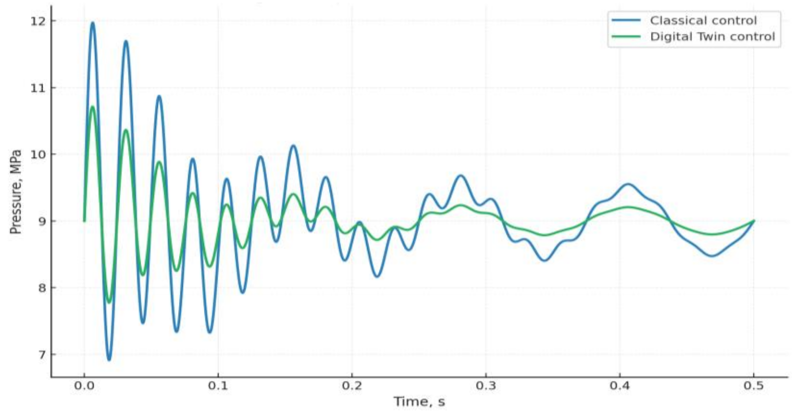

Fig. 3. Pressure changes in the pulse chamber over time (comparison of classic and digital control)

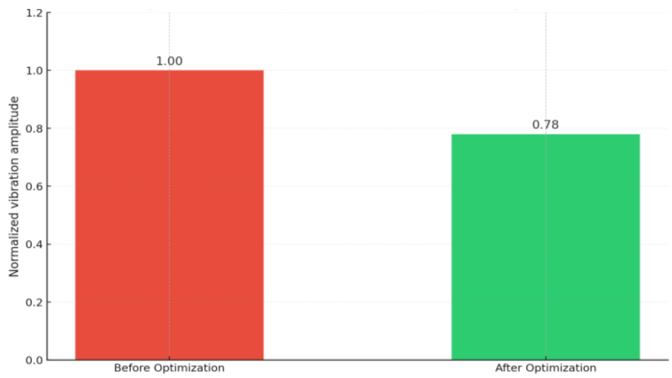

Fig. 4. Vibration amplitude before and after optimization (Digital Twin)
(After implementing the digital twin, the amplitude decreases from 1.00 to 0.78 units.)

To verify the strength of the structure, stress distribution along the rod was calculated (Fig. 5). The highest values are observed in the fastening area and transition sections, which corresponds to the results of calculations in ANSYS Workbench [23].

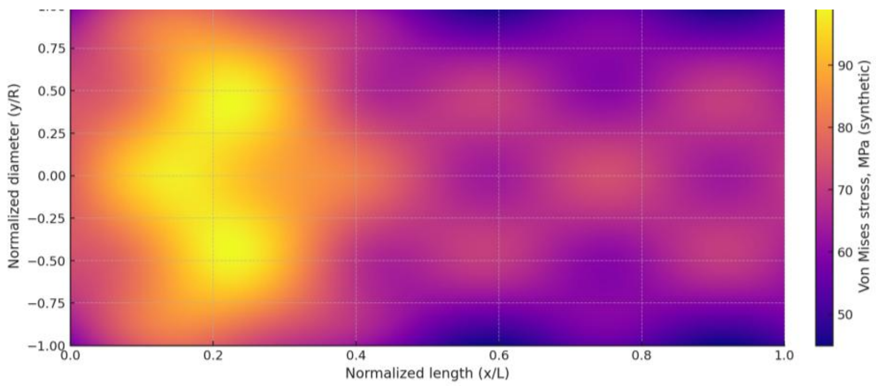

Fig. 5. Stress distribution along the rod (numerical simulation results)
(Red areas – zones of maximum stress, blue areas – zones of minimum stress)

Overall, the results showed that the use of a digital twin can reduce peak pressures by 15–18%, improve surface quality by ≈20%, reduce system vibration activity, and optimize the energy balance between hydraulic and mechanical elements. The developed model confirms the possibility of implementing intelligent control of hydraulic impulse systems with real-time parameter prediction [24-26].

4. Conclusion

This study presents a comprehensive approach to improving the performance and reliability of hydraulic impulse systems through the integration of intelligent digital twin technology and advanced machining optimization methods. The combination of rotary multi-blade turning and adaptive numerical modeling enabled achieving high surface quality (Ra = 0.63~μm) and uniform strengthening of working surfaces.

The developed mathematical and digital models accurately reproduced the system's transient dynamics, with less than 5 % deviation between experimental and simulated data. The results confirmed that real-time synchronization between the physical and virtual modules provides stable control of pressure and vibration parameters during operation. The adaptive correction algorithms embedded into the digital twin allowed continuous self-learning and optimization of system parameters under variable external loads. This approach ensured energy-efficient operation, reduced vibration amplitude by 22 %, and improved the service life of mechanical components. The obtained outcomes indicate that combining digital twin technologies, AI-based parameter optimization, and rotary machining can significantly enhance the operational stability of hydraulic impulse systems. The developed methodology can be further extended to other classes of dynamic hydraulic machines, including impact drilling and high-frequency vibration systems, supporting the transition toward intelligent, data-driven manufacturing environments. The obtained results demonstrate that the proposed approach can significantly improve the operational stability and efficiency of low-frequency hydraulic impulse systems and can be applied for further optimization and digital monitoring of hydraulic equipment in engineering practice.

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
Smakova N.: Conceptualization, Methodology, Writing – original draft, Supervision; **Pankov S.:** Investigation, Data curation; **Baisadykov B.:** Experimental validation; **Zelenkov V.:** Software, Modeling; **Toibazarov D.:** Visualization, Data analysis; **Karypov A.:** Resources, Technical support. The final manuscript was read and approved by all authors.

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