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**«Science & Research
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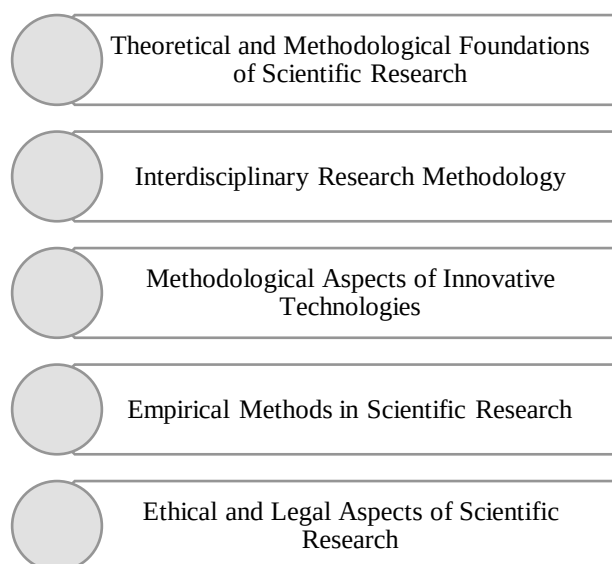


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STUDY OF THE AUTONOMOUS MECHATRONIC MODULE OF THE CAR CONTROL SYSTEM

Abstract. The aim of this work is to develop a design methodology for an autonomous electro-hydraulic mechatronic module (AMM) for the steering system of multi-axle heavy-duty vehicles (MTS OBG). This is driven by the limitations of traditional systems (mechanical and electro-hydraulic with centralized power), including low efficiency, complexity, weight, and reliability, especially in military applications. The research focuses on a hydrostatic AMM with volumetric speed control (variable-speed electric drive + fixed displacement pump) and an involute actuator mechanism for a constant transmission ratio. Efficiency and reliability are enhanced through modular design and volumetric control. The work includes a functional diagram, mathematical model, design methodology, and experimental verification on a test bench.

Key words: autonomous mechatronic module (AMM), electro-hydraulic steering drive (EHSP), multi-axle heavy-duty transport vehicle (MTS OBG), steering system, hydrostatic drive, volumetric control, involute actuator mechanism, mathematical modeling, design methodology.

Introduction. Multi-axle heavy-duty transport vehicles (MTS OBG) play a key role in transporting large indivisible loads for industry and military needs. Due to large loads and dimensions, the steering system of such machines must provide high maneuverability and precision. Traditional mechanical and electro-hydraulic drives with centralized power supply have significant drawbacks: low efficiency due to throttle control, heavy weight, complex kinematics, and long hydraulic lines, which reduce reliability, especially in military applications. A promising direction is the creation of autonomous electro-hydraulic mechatronic modules (AMM) for each steered wheel. AMMs offer higher efficiency (up to 70%) due to volumetric control, increased reliability through module independence, and ease of installation and maintenance. However, scientifically substantiated principles for constructing and designing such AMMs for MTS OBG are lacking. The aim of this work is to develop a design methodology for AMM based on studying the patterns of its functioning.

Methods and Materials. Based on the analysis of existing types of autonomous electro-hydraulic drives (with reversible pump, with reversing valve, hydrostatic type, volumetric-throttle), a functional diagram of a hydrostatic-type AMM was developed featuring a non-reversible fixed displacement pump, whose rotational speed is controlled by an electric motor, and a four-way, three-position electro-hydraulic directional control valve (EHDV) for flow reversal (Fig. 1).

A key feature is the use of an involute actuator mechanism instead of the traditional hydraulic cylinder with lever transmission. The involute mechanism provides a constant transmission ratio (radius R_{HO}) between the linear displacement of the pistons and the angular rotation of the wheel, reducing the required piston stroke and maximum fluid flow rate. Control algorithms were developed that ensure volumetric control of the wheel turning speed proportional to the error signal, maintaining minimum motor speed in the neutral position to reduce energy consumption and ensure reliability.

A detailed mathematical model of the AMM was created as a block structure (Fig. 2), considering the dynamics of the electric motor, pump characteristics (including leakage), fluid compressibility (considering undissolved air), hydraulic resistance of pipelines and the directional valve, actuator dynamics, and the elastic-damping properties of the tire.

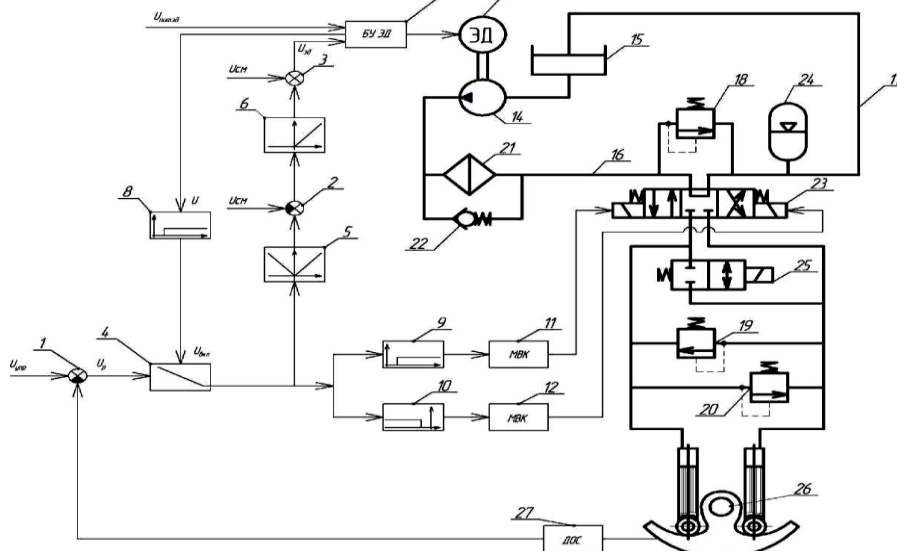


Fig. 1. Functional diagram of AMM

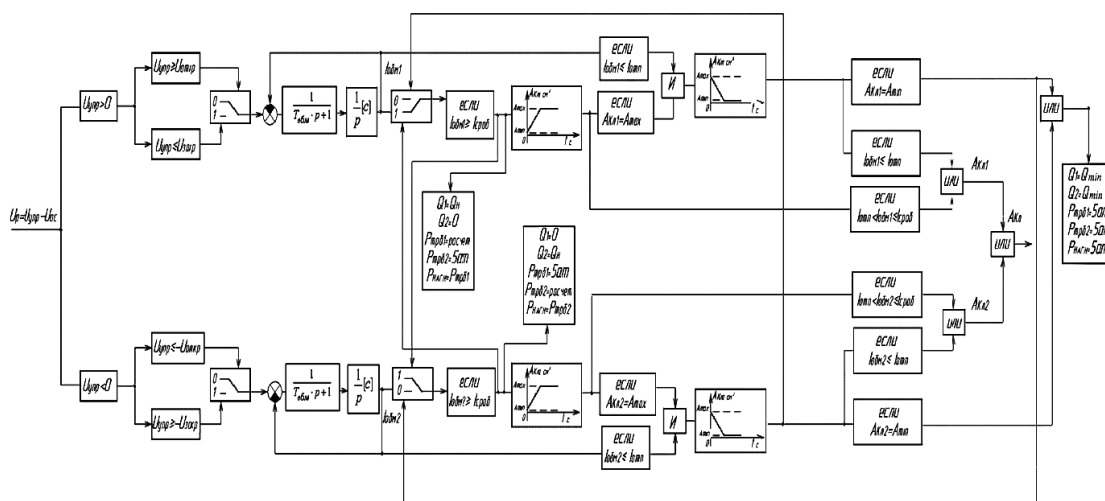


Fig. 2. Diagram of the generalized mathematical model of AMM

Modeling was performed in the Lazarus environment to analyze the dynamic characteristics of the system ("steering impulse", "steering reversal") under various loads and tire parameters, as well as to determine the optimal forward path gain (K_y) using Logarithmic Amplitude-Frequency Characteristic (LAFC) analysis. Based on the model, a design methodology for the AMM was developed, including the sequential calculation and selection of the pump, electric motor, directional valve, and determination of the control system gains. To verify the model and methodology, a test bench was created, and experimental studies of a prototype AMM were conducted.

Conclusions. The functional patterns and basic construction principles of the AMM for MTS OBG steering systems were established. A functional diagram of a hydrostatic-type AMM with an involute actuator mechanism was developed, and its advantages were substantiated. A mathematical model that adequately describes the dynamic processes in the AMM was created. Modeling confirmed the compliance of the AMM characteristics with the technical requirements (transient process time ~ 0.9 s, error < 2 deg, overshoot < 0.3 deg) and demonstrated the advantages of volumetric control – a direct relationship between power consumption and load. A universal design methodology for AMM was developed. Test bench experiments confirmed the adequacy of the mathematical model (convergence of results 12-15%) and the viability of the proposed technical solutions.