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EXPERIMENTAL TEST BENCH FOR INVESTIGATING THE CHARACTERISTICS OF A HYDRAULIC DRIVE WITH AN ANTI-SLIP DEVICE

ЕКСПЕРИМЕНТАЛЬНИЙ ВИПРОБУВАЛЬНИЙ СТЕНД ДЛЯ ДОСЛІДЖЕННЯ ХАРАКТЕРИСТИК ГІДРОПРИВОДУ З АНТИБУКСУВАЛЬНИМ ПРИСТРОЄМ

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Abstract. The article presents the development and methodological substantiation of a specialized experimental test bench for investigating the characteristics of a hydrostatic drive with an anti-slip control system. The study used hardware-in-the-loop (HIL) modeling methods, stall test (maximum-load test) and transient response test protocols. The scientific novelty lies in the comprehensive assessment of the transition from passive flow dividers to systems of individual electronic control of hydraulic motor displacement. The proposed control algorithms are expected to provide more effective damping of critical pressure pulsations than classical proportional controllers. The practical value of the work lies in providing accurate efficiency mapping, which creates a basis for optimizing energy saving in hybrid technology and the modern mobile machines.

Keywords: hydraulic drive, anti-slip device, experimental test bench, control algorithms, hydraulic motor.

Introduction.

Hydrostatic transmission of mobile machines is a system for transmitting mechanical energy from the prime mover to the drive wheels using hydrostatic pressure of a working fluid [1, 2]. Due to their ability to provide continuous and smooth speed control, extremely high specific power, low inertia of moving masses and the possibility of effective dynamic braking, hydrostatic transmissions have become the absolute standard for a wide range of mobile machinery [3]. This category includes agricultural tractors, combine harvesters, crop protection machines, construction machinery, skid steer loaders, excavators, road paving machines and modern unmanned ground vehicles [4, 5]. However, one of the most important and most complex problems that arise during the operation of such specialized machines in difficult conditions (off-road, snow, ice, viscous soil, rocky slopes) is the loss of traction of the wheels with the supporting surface, which inevitably leads to wheel slip [6, 7].

To fundamentally solve this problem, various anti-slip devices and traction control systems are being developed and implemented, which limit wheel slip and dynamically redistribute traction effort and torque between the wheels [4, 8]. The creation and implementation of anti-slip devices for hydrostatic transmissions remains a difficult scientific and technical task due to the nonlinearity of the characteristics of the interaction of the drive with the supporting surface. Anti-slip devices from the company "Poclain Hydraulics" demonstrate high efficiency [9, 10], but require adaptation to specific operating conditions and integration with existing domestic control systems. Therefore, the development of our own solutions and specialized stands for their testing is relevant.

Literature Review.

Modern hydrostatic transmissions of high-mobility vehicles are built according to a closed hydraulic circuit [11]. In such a circuit, the output of the main pump is connected directly to the input of the hydraulic motor (or a system of parallel-connected motors), and the output from the motor is returned directly to the pump suction, bypassing a large hydraulic tank. An additional make-up pump and make-up circuit are used to compensate for internal leaks and cooling.

Vehicle traction control fundamentally boils down to optimizing the micro- and macroscopic forces of interaction between a pneumatic tire (or track) and a supporting surface. In order to develop an adequate control algorithm on an experimental test bench, it is necessary to rely on mathematical models of the longitudinal dynamics of the vehicle and differential equations of the characteristics of the hydraulic circuit [12, 13].

To overcome the differential effect of parallel-connected hydraulic motors, several fundamentally different engineering and algorithmic approaches have been proposed and investigated over the past decade. Each of these approaches has its own advantages, disadvantages, and requires a specific experimental test bench architecture for full validation.

Conceptually, the simplest solution was to install flow dividers or special synchronizing valves in the hydraulic circuit [14]. These devices, often built on the basis of spool or gear dividers, forcibly branch the total flow from the pump into equal parts, regardless of the pressure drop across each individual hydraulic motor. The reviewed studies on a self-propelled plant protection machine showed that the introduction of a synchronizing valve allowed to significantly reduce wheel slip in field conditions. At the same time, at speeds of 3 km/h and 6 km/h, the wheel slip coefficient was acceptable 3.79% and 6.17%, respectively. However, the main and critical disadvantage of this method is the large throttle energy losses.

Another approach is to use the automotive anti-slip regulation system [15]. The anti-slip regulation system constantly monitors the angular velocities of the wheels using encoders, and when excessive acceleration of one of them is detected, it applies braking to the slipping wheel.

A similar principle is used in hydrostatic transmissions [4], but a mechanical or hydraulic brake mechanism is applied to the wheel slip. The brake creates artificial external resistance on the hydraulic motor shaft, which leads to a forced increase in pressure in the general hydraulic line. This restores the pressure drop and allows the wheels with good traction to again receive torque for movement. As a result, for unmanned ground platforms weighing more than 300 kg, it has been theoretically and practically proven that the use of an external braking system instead of classic flow dividers minimizes the internal pressure drop in the hydraulic equipment and allows for much more efficient overcoming of difficult terrain, reducing the overall energy consumption of the platform.

The most technological solution in the concept of mobile hydraulic control is the use of hydraulic motors with independent adjustable working volume (for example, Poclain Twin Lock systems [9], Danfoss H1 series technology [16]). The essence of this solution is to completely abandon energy-consuming throttling or mechanical braking with friction pads. If a wheel starts to slip, the microcontroller instantly sends a PWM signal to the servo valve of the corresponding hydraulic motor to reduce its working volume. In this case, the traction force on the slipping wheel is proportionally reduced, which exactly corresponds to its current low tire–road adhesion coefficient. The torque is dynamically redistributed between the axles or wheels according to their ability to realize traction, and without overheating the mineral oil.

Leading scientific research centers and industrial corporations were analyzed regarding the experimental test bench and parameters they investigated for hydrostatic transmissions of mobile machines (Table 1).

Thus, the nonlinearity of the working fluid requires an inevitable transition from simple PID controllers to advanced control systems based on fuzzy logic, differential speed algorithms and active suppression systems of uncontrolled disturbances.

Table 1. Analysis of the main achievements of research centers in the field of hydrostatic transmissions of mobile machines

Research Center	Research direction	Experimental base	Main achievements
Faculty of Mechanical Engineering and Marine Technology, University of Rostock [17]	Improvement of hydrostatic transmission control algorithms, compensation of nonlinearities, spatial trajectory tracking	A sophisticated cyber-physical test bench for testing electro-hydraulic systems in a HIL environment	The fundamental inefficiency of classic PID controllers due to the nonlinearity of the fluid has been experimentally proven. Optimal control, methods of active disturbance suppression and tracking differentiators have been implemented
School of Mechanical Engineering, University of Jinan [14]	Preventing wheel slip of agricultural machinery using valve equipment	Field test platform with laser measurement of actual distance traveled and wheel speed	Forced steering has been proven to reduce the slip coefficient from 6.17% to a stable 3.79% at an operating speed of 6 km/h, increasing the required stability
Faculty of Mechanical Engineering, Military University of Technology [4]	Mobility of unmanned platforms on rough terrain. Development of high traction forces on unstable soils	Computer simulation modeling followed by bench validation of hydraulic motor traction forces	It has been proven mathematically and practically that external electro-hydraulic braking outperforms flow dividers in terms of energy efficiency
College of Engineering, Nanjing Agricultural University [18]	Grey-box modelling of electro-hydraulic lifting mechanisms and intelligent algorithms with anti-slip device	Experimental test bench with proportional solenoid control valves	Using Whale Optimization Algorithm to identify hidden parameters. Extreme control accuracy achieved (RMSE of errors was only 0.33 mm)
Poclain / Danfoss firm innovations [9, 16]	Development of commercial systems CreepDrive, H1 traction control, Twin Lock	Certified Application Development Centers with truck dynamometers	esting of independent electronic control of engine displacement. Successful testing on gravel slopes, avoiding engine stall effects
College of Mechanical and Electronic Engineering, Shandong Agricultural University [19]	Analysis of the shifting quality of hydrodynamic continuously variable transmissions during critical hydraulic system failures	A full-fledged dynamometer for testing hydrodynamic continuously variable transmissions without starting the internal combustion engine	A safe methodology for testing hydraulic system failures on a bench without destroying a real, expensive tractor transmission has been created
AVIC The First Aircraft Institute [20]	Creation of miniature electrohydrostatic braking systems for aircraft with anti-slip algorithms	Inertial test bench with semi-real-life simulation of aircraft aerodynamics	Implementation of backstepping surfaces and on/off valves to increase reliability in mineral oil contamination conditions

Modern developers are trying to rigidly separate the hydraulic power unit and software logic, transferring the lion's share of algorithm testing to a virtual environment with hardware locking. This will allow a real axial piston pump and motors to be physically rotated on the experimental test bench, while the inertia of a multi-ton machine, dynamic soil resistance and the percentage of tire wheel slip are calculated and simulated in real time by a powerful computer. At the same time, it applies the appropriate physical load to the hydraulic motor shafts through high-speed loading devices.

Research Methodology.

The main goal of the article is to substantiate and develop the concept of an experimental test bench for a comprehensive study of working processes in the hydraulic drive of a mobile machine with an anti-slip device.

The experimental test bench is designed according to the modular principle, which allows to study both individual elements (pump, hydraulic motors, valve equipment) and the entire system as a whole. The primary power source of the test bench is a power-and-drive module that simulates the internal combustion engine of the vehicle. The use of real diesel engines in laboratories is associated with environmental problems and the complexity of control. Therefore, modern stands use powerful industrial asynchronous AC electric motors (with a power of 5 to 90 kW, depending on the scale of the transmission), which are controlled by high-precision Variable Frequency Drives. This allows you to programmatically create various dynamic torque characteristics, simulating, for example, turbocharger lag or a reduction in diesel-engine speed under sudden hydraulic overload.

For full testing of the anti-slip device, it is critical to be able to independently and extremely quickly change the load on each output hydraulic motor, physically simulating sharp spatial changes in the tire–road adhesion coefficient [18]. To do this, the output shafts of the hydraulic motors are rigidly connected to the loading devices.

A stand for testing highly dynamic fast-moving processes, such as the transition from normal operation to transient wheel slip, must record changes in indicators with a sampling frequency of at least 1 kHz, and ideally up to 5 kHz. The basic list of necessary precision sensors must include: pressure measurement, flow measurement, speed and position sensor, and torque measurement.

The study of modern high-speed proportional valves, which are widely used in anti-slip device, requires perfectly clean oil. Servo valves are extremely sensitive to micro-contamination, which can cause spool jamming [21, 22]. Strict industry standards categorically require the use of stands capable of maintaining oil cleanliness two ISO code levels higher than in a conventional working machine in the field. This is technologically achieved by installing special Hydrostatic Filter Groups (e.g. 9U-5899) with duplex filters (10 μm and 5 μm filtration) in the pressure and drain lines with visual and electrical clogging indication. In addition, since throttling during anti-slip device operation generates a huge amount of waste heat, the stand must have a main cooling system. It consists of water-oil heat exchangers or air radiators controlled by a PID thermostat, which guarantees the absolute maintenance of the liquid temperature within 50±2 ° C. Only under such conditions is the constancy of the kinematic viscosity of mineral oil ensured during experiments lasting many hours.

A modern experimental test bench is not just a set of drives, but a complex cyber-physical complex controlled by programmable logic controllers. To test the anti-slip algorithm, a real commercial control unit is usually installed on the stand. In this case, the Real-Time Target Machine calculates the full multi-body dynamics of the mass of the tractor or loader, reads the hydraulic motor speeds with microsecond-level timing resolution from the stand, mathematically calculates the virtual movement of the chassis and the tire–ground contact conditions. After that, the HIL system generates a control command for the dynamometers, instantly increasing or decreasing the physical resistance on the shaft, realistically

reproducing the transition to a low-adhesion surface in laboratory conditions [23]. Next, the measuring system monitors how the anti-slip device controller reacts to this sudden event.

Based on the analysis of the research methodology, the main recommendations for systems and subsystems for the configuration of the experimental test bench were formulated (Table 2).

Table 2. Recommended systems and subsystems for the implementation of the experimental test bench

Main subsystems of the experimental test bench	Recommended specifications	Purpose in the experiment
Power and Drive Module	Electric motor, 5-90 kW, with variable-frequency drive control, 0-3000 rpm	Simulation of a car's internal combustion engine taking into account the nonlinear torque curve and speed drops
Dynamic Load Unit	Electromechanical servomotors with dynamometers	Highly dynamic simulation of ground resistance, instantaneous changes in tire–road adhesion coefficient
DAQ Module	Sampling frequency from 1 kHz, 16-bit analog-to-digital converter, digital buses CAN-bus, EtherCAT	Reliable synchronization of data collection of pressure, speed and micro-displacements of the main pump swash plate
Hydraulic Station	Working pressure 250-400 bar, flow up to 200-380 l/min, ultrafiltration ISO 16/13	Ensuring stable physical, chemical and temperature conditions for the operation of the hydrostatic transmission.

To implement the control of the experimental test bench processes on a programmable logic controller, the following basic structure of the anti-slip device control algorithm was developed:

1. System initialization (sensor polling, operating pressure check);
2. Main measurement cycle (with a period of 10 ms);
2.1. Reading the speeds of the hydraulic motors;
2.2. Calculation of the average theoretical speed;
2.3. Determination of the slip coefficient for each wheel;
3. Conditions for turning on the anti-slip device: IF the permissible slip is exceeded, THEN we generate a control signal for the valves of the anti-slip device of the corresponding wheel and correct the supply of the adjustable pump to minimize pressure losses, OTHERWISE we support the nominal flow distribution mode.
4. Return to step 2.

Furthermore, the modular architecture of the experimental test bench provides hydraulic ports and software interfaces for the direct integration of energy recovery systems. To fully explore energy recuperation within hydraulic drives, hydropneumatic accumulators and advanced directional control valves can be connected to the main circuit. This hardware flexibility allows for the physical simulation of regenerative braking, where the kinetic energy of the virtual vehicle, calculated by the HIL system, is converted back into hydraulic pressure and stored.

Thus, based on the analysis, complex requirements for the hardware and software components of the experimental test bench have been formed. The use of precision measuring equipment in combination with high-speed servo valves and dynamometers enables accurate reproduction of complex off-road operating conditions in laboratory conditions. The described control algorithm provides flexibility of settings for testing various strategies for redistribution of traction force.

The practical implementation of the proposed methodology will allow not only to investigate the effectiveness of commercial anti-slip devices, but also to develop and validate our own, adapted to domestic operating conditions, hydrostatic transmission control algorithms. The next step is to develop a scheme of an experimental test bench and analyze the required accuracy of the hydraulic drive characteristics in wheel slip simulation modes.

Results.

After completing the stage of theoretical justification of the experimental test bench configuration, its scheme was developed. The general view of the experimental test bench scheme during test execution and recording of operating parameters is shown in Fig. 1. This allows you to visualize the layout of key hydrostatic transmission lines, loading devices and an array of measuring sensors involved in the study.

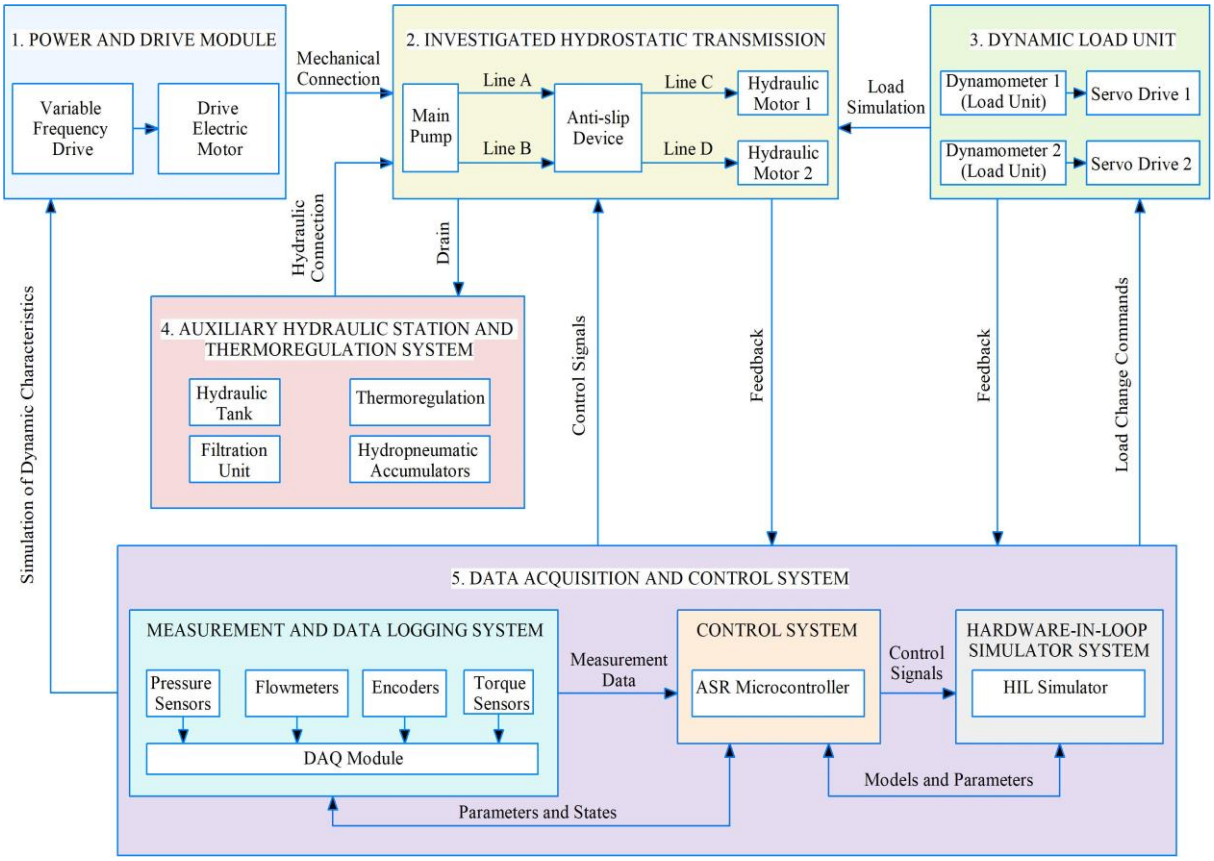


Fig. 1. Scheme of the experimental test bench for studying the characteristics of a hydraulic drive with an anti-slip device.

To ensure high accuracy of verification of nonlinear mathematical models, the use of modern high-speed analog-to-digital converters and precision sensors is envisaged. Fast transient processes that occur during sudden wheel slip and at the moment of anti-slip device activation are recorded.

Table 3 summarizes the key parameters studied on the experimental test bench, provided by the measuring equipment under different loading conditions and simulated tire–road adhesion coefficient. These results serve as an empirical basis for assessing the effectiveness of the proposed control algorithms.

The main experimental procedures include stall testing, transient-response testing, simulated wheel-slip testing, efficiency mapping, and energy-recovery testing. Stall test is a classic, but extremely important procedure for verifying the maximum traction capacity of hydraulic and mechanical systems without actual vehicle movement. On the bench, the hydraulic motors are forcibly blocked, the pump displacement is brought to maximum, and

the drive electric motor is accelerated to maximum speed. During the study, the maximum pressure achieved in the system is recorded, the correct operation of the pressure relief valves is checked, and the case drain is measured. To ensure the reliability of the results and prevent mineral oil degradation, the temperature of the working fluid during the test is strictly controlled by bench automation (maintained at about 50°C). This test will be used to verify whether the system can withstand the critical peak loads that occur when the traction control device redistributes 100% of the traction force to one wheel with a high tire–road adhesion coefficient to the ground.

Table 3. Investigated parameters on the experimental test bench

Measured parameter	Sensor type	Measurement range	Accuracy
Pressure in the pressure and return lines	Strain gauge pressure transducer	0...40 MPa	±0,5%
Hydraulic fluid flow rate	High-pressure turbine flow meter	5...150 l/min	±1,0%
Hydraulic motor speed	Incremental encoder	0...3000 rpm	±2 rpm
Hydraulic fluid temperature	Thermal resistance	-20...+100 °C	±0,5 °C

Transient response testing and slip simulation involves operating the stand in the basic and most informative mode for studying Traction Control systems. The complex test protocol involves bringing the hydrostatic transmission to a stationary cruising mode with high symmetrical resistance, after which the HIL system instantly (10–50 ms) minimizes the load on one of the hydraulic motors, simulating a sudden loss of traction. The provoked uncontrolled slip causes a sharp drop in pressure and stops the support motor. Having identified a kinematic mismatch in the form of a critical increase in differential speed, the anti-slip drive instantly initiates countermeasures - reduces the displacement of the hydraulic motor. The stand equipment at high speed records the time of restoration of traction and the dangerous amplitude of pressure pulsations, which, thanks to the use of modern control algorithms, is damped 2.5-5 times more effectively compared to classic proportional regulators.

The experimental test bench additionally provides automated construction of multidimensional efficiency maps by testing the object in the entire matrix of pressures and speeds by recording the balance between input and useful output power. Highly accurate assessment of energy losses of the anti-slip device itself is critical for the latest electric forklifts and hybrid equipment. Given the specific balance of power, each joule of stored hydraulic energy directly extends the duration of autonomous operation of such machines from the battery. To comprehensively investigate this process, a dedicated energy recuperation testing protocol will be implemented. During simulated braking or downhill movement, the dynamic load units will operate in a driving mode, transferring mechanical energy back to the hydraulic motors, forcing them to act as pumps. The measuring system will evaluate the efficiency of capturing this reverse fluid flow into hydropneumatic accumulators and record the transient responses of the mechatronic valves during the rapid switch between traction and recuperation modes.

As a result, the data obtained after experimental studies will be used to develop and refine nonlinear mathematical models of the hydraulic drive of a mobile machine in simulation environments.

Conclusions.

The creation of a specialized experimental test bench for studying the characteristics of a hydraulic drive with an integrated anti-slip device is an extremely complex multidisciplinary engineering task. This task combines the laws of ultra-high-pressure hydraulics, the applied theory of complex nonlinear spatial control of multi-mass systems, and the most modern information cyber-physical technologies. An analysis of scientific and technical sources over the past decade has been conducted, noting a clear transition from hydromechanical compensators (such as passive flow dividers) to intelligent high-speed systems for the individual electronic control of the working volume of each hydraulic motor.

It should be emphasized that this article primarily focuses on the methodological development, architectural design, and hardware validation of the experimental test bench itself. The developed hardware and software complex proves its suitability and readiness for a comprehensive assessment of such intelligent systems. The proposed control algorithms are expected to provide more effective damping of critical pressure pulsations than classical proportional controllers. Executing the proposed stall test and transient response protocols will provide extensive empirical data sets to evaluate the dynamic damping of critical pressure pulsations under simulated loss of traction.

In addition to assessing traction characteristics, the created stand opens up wide opportunities for automated efficiency mapping and the accurate measurement of measurement of small energy losses within the system. This creates a reliable scientific and technical basis for the further improvement of energy recovery systems in modern hydraulic drives, which is a critically important stage in the design of energy-efficient hybrid technologies and modern mobile machines. Ultimately, the developed test rig forms a robust experimental foundation for future comprehensive studies on energy recuperation in mechatronic hydraulic drives, enabling the practical validation of intelligent control strategies for regenerative braking.

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ЕКСПЕРИМЕНТАЛЬНИЙ ВИПРОБУВАЛЬНИЙ СТЕНД ДЛЯ ДОСЛІДЖЕННЯ ХАРАКТЕРИСТИК ГІДРОПРИВОДУ З АНТИБУКСУВАЛЬНИМ ПРИСТРОЄМ

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Анотація

Робота присвячена вирішенню складної мультидисциплінарної інженерної задачі – розробці та дослідженню спеціалізованого апаратно-програмного експериментального випробувального стенда для тестування гідростатичних трансмісій з інтегрованими антибуксувальним пристроєм. Головною метою є обґрунтування та розробка концепції експериментального випробувального стенду для комплексного дослідження робочих процесів у гідроприводі мобільної машини з антибуксувальним пристроєм. У процесі дослідження застосовано комплексний підхід, що поєднує закони гідравліки, теорію просторового керування багатомасовими системами та сучасні кіберфізичні HIL-технології. В процесі дослідження також проаналізовано продукцію інноваційних фірм Poclain та Danfoss, зокрема, їхні розробки: CreepDrive, H1 traction control, Twin Lock. Для верифікації параметрів реалізовано специфічні протоколи: тести на утримання з жорстким температурним контролем для оцінки внутрішніх витоків; випробування на перехідний відгук, які імітують раптову втрату зчеплення колеса з ґрунтом шляхом миттєвого скидання опору навантажувального пристрою; а також алгоритми побудови багатовимірних карт ефективності. Проведено ґрунтовний аналіз тенденції переходу від класичних пасивних гідромеханічних компенсаторів до швидкодійних систем індивідуального електронного керування робочим об’ємом гідромоторів. Наведені рекомендації систем із технічними характеристиками для комплектації експериментального випробувального стенду, а також діапазони та точність досліджуваних параметрів. Отримані результати створюють міцне науково-технічне підґрунтя для вдосконалення систем рекуперації енергії в гідравлічних приводах. Точний облік енергетичного балансу є критично важливим для розробки новітньої мобільної машини, де кожен збережений джоуль гідравлічної енергії прямо пропорційно продовжує час автономної роботи машини від акумуляторних батарей.

Ключові слова: гідропривод, антибуксувальний пристрій, експериментальний випробувальний стенд, алгоритм керування, гідромотор.