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ANALYSIS OF VOLUMETRIC REGULATION OF HYDRAULIC PUMPS IN HYDROSTATIC SYSTEMS

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Vesna Jovanović[1], Dragoslav Janošević[1], Jovan Pavlović[1], Nikola Petrović[1], Đorđe Lazarević[2]

[1] University of Niš, Faculty of Mechanical Engineering, Republic of Serbia
[2] University of Niš, Faculty of Electronic Engineering, Republic of Serbia

ORCID iDs: Vesna Jovanović https://orcid.org/0000-0001-9252-7894
Dragoslav Janošević https://orcid.org/0009-0001-1771-3985
Jovan Pavlović https://orcid.org/0000-0002-8825-7307
Nikola Petrović https://orcid.org/0000-0002-9166-1263
Đorđe Lazarević https://orcid.org/0000-0002-6391-9706

Abstract. *The paper presents the results of the conducted researches related to the analysis of the parameters of the drive system, the crawler hydraulic excavator, with hydraulic pumps with collective regulation according to the criterion of constant hydraulic power and the regulator of ideal hyperbolic characteristics. A crawler excavator weighing 16,000 kg with a three-member manipulator with boom, arm and bucket with a volume of 0.6 m3 was tested. The paper discusses the principles of volumetric regulation of hydrostatic systems, which is achieved by changing the specific flow rate of the hydraulic pumps. For pumps with constant specific flow rates, regulation is performed by reducing the flow through the hydraulic motors, which increases the pressure in the pump's delivery line and is controlled by a safety valve. This method, however, can lead to oil heating and energy loss. In contrast, pumps with variable specific flow rates use modular regulators that adjust the pump's characteristics based on system parameters, ensuring efficient operation under varying load conditions. The study's findings indicate that the use of hydraulic pumps with combined power regulation and an ideal hyperbolic characteristic regulator allows for the maintenance of constant hydraulic power even with changing loads. This regulation method ensures efficient use of the engine's power and prevents motor overload, enhancing the overall performance and longevity of the excavator. The research underscores the significance of proper hydraulic pump regulation in achieving optimal machine efficiency and durability.*

Key words: *Drive system, regulation, hydraulic pumps.*

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Corresponding author: Vesna Jovanović
University of Niš, Faculty of Mechanical Engineering, Aleksandra Medvedeva 14, 18000 Niš, Republic of Serbia
E-mail: vesna.jovanovic@masfak.ni.ac.rs

1. INTRODUCTION

In construction, agriculture, and industry, mobile machines with regulated hydraulic drives have the widest application. The working conditions and the fulfillment of the basic functions of these machines require the ability to widely regulate movement and manipulation parameters [1,2]. The advantages of control and the agility of the regulation system's response to the load of the drive mechanisms have become the focus of research [4,5]. Compared to mechanical or electrical transmissions, the energy efficiency of hydraulic systems is relatively low, so much work has been invested in improving energy efficiency [6-8]. Adapting the supply flow to actual loads during movement and manipulation tasks of machines, such as flow matching systems [9,10], hydraulic transformers [11], load sensing systems [12-14], and pump-controlled cylinders [15,16], are some of the potentially useful solutions. Generally, the supply flow can be adjusted in two ways [17]. The first way is that a variable speed motor drives a fixed displacement pump, thus determining the delivered flow.

In that case, the speed regulation dynamics are basically determined by the motor inertia. Another solution is hydraulic systems with a variable displacement pump driven by either an internal combustion engine or an electric motor at constant speeds, where the supply flow can be changed by varying the displacement volume of the pump. In these systems, the regulation of hydraulic pumps is predominant. The most commonly used pumps with variable displacement are the swash plate and bent axis types.

Due to the lower inertia of the rotating mass in the swash plate design [18], a wider range of hydraulic system parameters is achieved, making it a good candidate for applications requiring fast dynamics. To achieve better performance, mathematical models and various feedback control methods for managing nonlinear systems have been developed.

In the paper [19], emphasis is on the performance robustness of an open circuit axial piston pump with respect to both variations in the internal physical parameters of the pump as well as the type of application-dependent load which the pump is expected to drive. The pressure control is established by means of cascade control utilizing four control loops, with the outer being the pump pressure and then, in succession, the swash plate rotation, the spool position, and the voice coil current.

The paper [20] utilizes robust control methods to design and analyze control systems for a variable-displacement hydraulic pump. The system studied features a variable-displacement swash-plate hydraulic pump with a constant drive speed model. The system's input is the current that actuates the control valve position, while the output is the pump's discharge pressure. Both a PD controller and an H-infinity two degrees-of-freedom controller were designed. The robustness of these two designs is compared using the frequency domain analysis. Time domain results indicate that the PD controlled system outperforms the two degrees-of-freedom controlled system. Additionally, time domain simulations demonstrate an improved robustness to parametric variations.

The paper [17] focuses on the supply pressure control problem for a self-supplied variable displacement axial piston pump subjected to unknown time-varying load flow disturbances. Due to the self-supply mechanism of the pump, the mathematical model exhibits a switching characteristic, and one of the two subsystems is non-minimum phase, complicating the controller design. A control strategy using the method of output redefinition combined with a switching control scheme is proposed. By defining a new output, the new system becomes minimum phase with respect to the revised output, facilitating a feedback controller design.

Based on the proposed load flow disturbance observer, a new desired output is proposed to reduce tracking errors in the presence of time-varying load flow disturbances. Two feedforward controllers along with a switching scheme are also proposed, and a common feedback controller is used to stabilize the system. The stability of the whole system is proved. Experimental results are provided to illustrate the effectiveness of the proposed controller.

This paper presents the results of the conducted researches related to the analysis of the parameters of the drive system, the crawler hydraulic excavator, with hydraulic pumps with collective regulation according to the criterion of constant hydraulic power and the regulator of ideal hyperbolic characteristics. The study's findings indicate that the use of hydraulic pumps with combined power regulation and an ideal hyperbolic characteristic regulator allows for the maintenance of constant hydraulic power even with changing loads. This regulation method ensures the efficient use of the engine's power and prevents the motor overload, enhancing the overall performance and longevity of the excavator. The research underscores the significance of proper hydraulic pump regulation in achieving optimal machine efficiency and durability.

In the mining and construction sectors, earthmoving equipment is essential. Hydraulic excavators are common examples [21]. With the classic five-member configuration of the kinematic chain, a crawler support movable member L_1, a rotating platform L_2, a manipulator with boom L_3, arm L_4, and bucket L_5, hydraulic crawler excavators (Fig. 1a) carry out a typical digging function. An excavator's hydrostatic drive system with a crawler support movable mechanism is generally composed of the following components [22]: diesel engine 1 (Fig. 1b), hydraulic pump 3, main distributor 4, integral crawler drive c_1 with hydraulic motor 5, reducer 6, and sprocket 7.

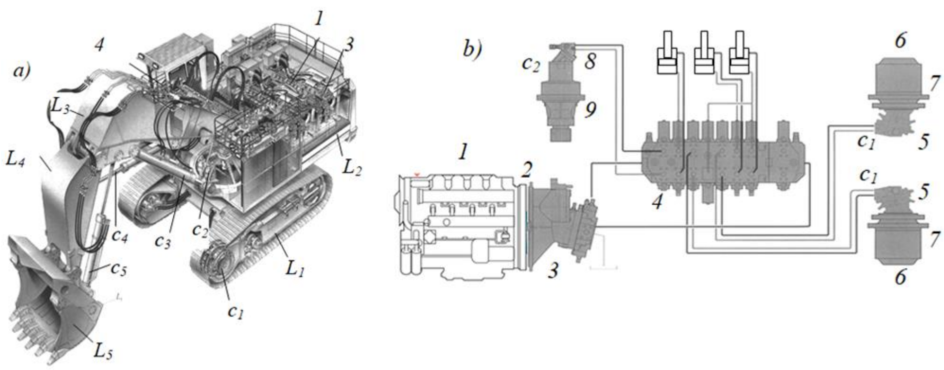

Fig. 1 Crawler excavator: a) physical model, b) drive system

Hydraulic cylinders of boom c_3, arm c_4, and bucket c_5 are actuators of the manipulator's drive system. The rotary platform drive mechanism's actuator is an integral transmission made up of a reducer 9 and a hydraulic motor 8. In hydrostatic systems, hydraulic pumps typically convert the mechanical power characteristics that are received into hydraulic power parameters, which are subsequently transferred to the oil as the carrier. The torque M_p at the hydraulic pump's input shaft and the rotational speed n_p are the input mechanical power parameters N_p. The flow rate Q_p and the oil pressure p in the pump's pressure line are the output hydraulic power parameters.

2. HYDRAULIC PUMP REGULATION

The specific flow rate q_p, volumetric efficiency η_{pv}, and mechanical efficiency η_{pm} of the hydraulic pump are the fundamental parameters of its transfer function. The working volume of the hydraulic pump's transformation mechanism, which may theoretically suction and discharge oil with no losses per revolution of the pump's input shaft, is known as the specific flow rate, or q_p. The specific flow rate determines the size of the hydraulic pump. The following equations provide the hydraulic pump transfer functions, which relate the input and output parameters [22]:

- the low in the pressure line of the hydraulic pump:

$$Q_p = \frac{q_p \cdot n_p}{1000} \eta_{pv} \quad [l/min] \tag{1}$$

- the rotational speed of the hydraulic pump's shaft:

$$n_p = \frac{1000 \cdot Q_p}{q_p \cdot \eta_{vp}} \quad [min^{-1}] \tag{2}$$

- the torque at the input shaft of the hydro pump:

$$M_p = \frac{q_p \cdot p}{2 \cdot \pi \cdot \eta_{pm}} \quad [Nm] \tag{3}$$

- the power required to drive the hydraulic pump:

$$N_p = \frac{Q_p \cdot p}{60 \cdot \eta_{pv} \cdot \eta_{pm}} = \frac{Q_p \cdot p}{60 \cdot \eta_{pu}} \ [kW], \tag{4}$$

where: q_p - specific flow rate of the pump, η_{pv} - is the volumetric efficiency of the pump, η_{pm} - is the mechanical efficiency of the pump, Q_p - is the pump flow rate [l/min], p_p- is the pressure in the pump pressure line [MPa], and η_{pu}=η_{pv}=η_{pm} is the overall efficiency of the pump.

Excavators with hydrostatic systems can adjust their fundamental characteristics, such as the pressure and flow, based on criteria that match variations in the machine's operating parameters. In principle, there is the damping and volumetric regulation of hydrostatic systems.

3. VOLUMETRIC REGULATION OF HYDRAULIC PUMPS

Volumetric regulation of hydrostatic systems is achieved by altering the specific flow rate of hydraulic pumps. In fixed displacement hydraulic pumps, regulation is achieved by reducing the flow to the hydraulic motor, which is done by decreasing the flow cross-sections of the distributor. This results in an increase in pressure in the working line of the hydraulic pump, which is regulated by a safety valve, thereby reducing the supply flow to the hydraulic motor and consequently the number of revolutions of the output shaft [23]. However, the oil heats up during this process, which is called "throttling the oil stream," which results in some of the hydrostatic system's power being lost and transformed into heat.

The regulation of variable displacement hydraulic pumps is performed using special modular devices – regulators that are integrally connected with the hydraulic pump [24].

The characteristics of the regulators are adapted to different operating conditions of the system. The signals on which the regulators base their characteristics are either predefined or depend on the system's functional parameters. They can be mechanical, hydraulic, electrical, or electronic in nature.

The following equation represents the hydraulic pump regulation based on the constant hydraulic power criterion:

$$N_h = \frac{p \cdot Q}{60 \cdot \eta_u} = k_n \cdot p \cdot Q = const\,, \tag{5}$$

where: p - pressure of the hydraulic pump, Q-flow of the hydraulic pump, k_n-constant. By changing the flow rate of the hydraulic pump given by the expression:

$$Q = \frac{q_p \cdot n_p}{1000} \eta_{vp} = k_q \cdot q_p \cdot n_p \tag{6}$$

in equation (5) it is obtained:

$$N_h = k_n \cdot p \cdot k_q \cdot q_p \cdot n_p = k_h \cdot p \cdot n_p \cdot q_p = const, \tag{7}$$

where: n_p - number of revolutions of the input shaft of the hydropump, q_p - specific flow of the hydropump, k_h - constant.

If for further analysis it is assumed that the number of revolutions of the hydropump n_p is equal to the number of revolutions of the engine n_{en} (n_p=n_{en}=$const$) at its maximum power, according to equation (7), the regulator of the hydropump according to the criteria the constant hydraulic power should enable a hyperbolic change in the specific flow q_p of the hydropump depending on the change in pressure p in the pressure line of the hydropump, expressed by the equation:

$$q_p = \frac{N_h}{k_h \cdot p \cdot n_p} = \frac{k}{p} = f_q(\alpha) \tag{8}$$

where: α - parameter on which the change in the specific flow of the hydraulic pump depends, k - constant.

Enabling the use of the maximum engine power, or the hydraulic power of the system, under various functional parameters (such as resistances and movement speeds) during the machine's work cycle is one of the main needs of the hydrostatic system. Drive system pumps with volumetric regulation and an optimal hyperbolic characteristic regulator based on the requirement of constant hydraulic power are standard on modern hydraulic excavators. With the help of an integrated power divider 3.12 (Fig. 2a, b) in the form of gears, an elastic connection 2, a diesel engine 1 powers these hydraulic pumps (Fig. 2), which are two identical pumps housed in the same housing.

In these hydraulic pumps, the regulator consists of: the cylinder 3.1 (fig. 2b) with a differential piston 3.2 supported by a spring 3.6 and a two-armed lever 3.4. The pivot block of the hydraulic pump 3 is connected by a linkage 3.7 to the differential piston 3.2.

A small piston 3.3 is transversely placed within the piston 3.2. The chamber on the front side of the piston 3.3 is connected to the pressure lines of the hydraulic pumps through lines in piston 3.2, the cylinder chamber 3.1, and the pressure manifold 3.11.

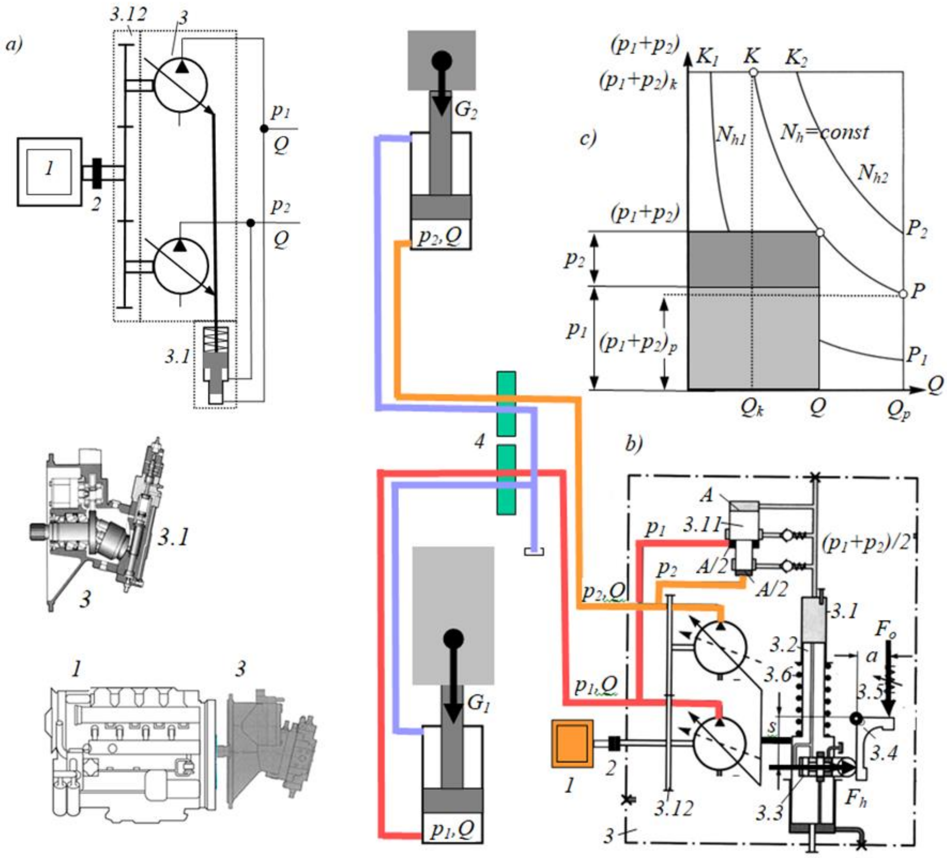

Fig. 2 Volumetric regulation of hydraulic pumps [22]: a) double hydraulic pumps with combined power regulation, b) the regulator, c) regulation with an ideal hyperbolic characteristic regulator

On one arm of the two-armed lever 3.4, one side is acted upon by the small piston 3.3 with the force created by the pressure in the pressure lines of the hydraulic pumps acting on the piston's front. On the other side, the same arm of the lever 3.4 is acted upon by the force of spring 3.5. The regulation signal is the sum of pressures (p_1 + p_2) in the pressure lines of the hydraulic pumps, which is created in the pressure manifold 3.11, for which the balance condition applies:

$$p \cdot A = p_1 \frac{A}{2} + p_2 \frac{A}{2} \quad \Rightarrow p = \frac{p_1 + p_2}{2} \tag{9}$$

On the front of piston 3.3, with a surface area A_k, the regulator of the hydraulic pump acts a pressure of $(p_1+p_2)/2$, creating a force.

$$F_h = \frac{p_1 + p_2}{2} A_k \tag{10}$$

so, according to the equilibrium condition of the lever 3.4, the displacement of the piston 3.2 of the regulator is equal to:

$$s = \frac{F_o \cdot a}{A_k} \cdot \frac{2}{p_1 + p_2} = \frac{k_r}{p_1 + p_2} = f_1(\alpha) = f_2(q_p) \tag{11}$$

The piston 3.2 is connected to a linkage that joins the blocks of the hydraulic pumps. Consequently, with the movement s of piston 3.2, the angle of rotation of the hydraulic pump blocks remains the same, ensuring that the specific flows q_p of the hydraulic pumps are identical.

Within the range of the hydraulic pump regulation, determined by the pressure $(p_1+p_2)_p$ at the start and $(p_1+p_2)_k$ at the end of regulation, the flow Q of the hydraulic pumps remains constant and changes hyperbolically with the change in the sum of the pressures (p_1+p_2) at a constant hydraulic power (Fig. 3c):

$$N_h = \frac{(p_1 + p_2)_p \cdot Q_{max}}{60 \cdot \eta_{pu}} = \frac{(p_1 + p_2) \cdot Q}{60 \cdot \eta_{pu}} = \frac{(p_1 + p_2)_k \cdot Q_{min}}{60 \cdot \eta_{pu}} = const \tag{12}$$

By changing the force in the spring 3.5 of the regulator, the initial pressure $p_p = (p_1 + p_2)_p$ of the regulation (points P1, P2) is altered, thereby changing the hydraulic power (N_{h1}, N_{h2}) encompassed by the regulation. At the same time, the pressure $p_k = (p_1 + p_2)_k$ at the end of regulation (points K1, K2) remains the same [25][26].

4. ANALYSIS

A comparative study of the hydraulic power parameters of the same model of excavator with dual fixed and variable displacement hydraulic pumps brought to light the significance of controlling the hydraulic pumps of the drive system of hydraulic excavators. The crawler excavator that was put through the test weighed 16,000 kg and included a three-part manipulator that included a boom, arm, and bucket with a 0,6 m^3 capacity. The hydraulic power N_h of the hydraulic pumps, the number of rotations of the diesel engine, and the pressures p_1, p_2, and flow rate Q in the hydraulic pumps' pressure lines were all measured and calculated during the testing process while performing the following manipulation tasks: excavating, moving, unloading category III soil, and returning to the new digging position.

In excavators with dual fixed displacement hydraulic pumps (fig. 3a), the utilized power (fig. 3b) of the drive motor, i.e., the hydraulic power of the hydraulic pump, is proportional to the system pressure and the magnitude of the resistance. Full utilization of the drive motor power occurs only when both drive mechanisms are in motion.

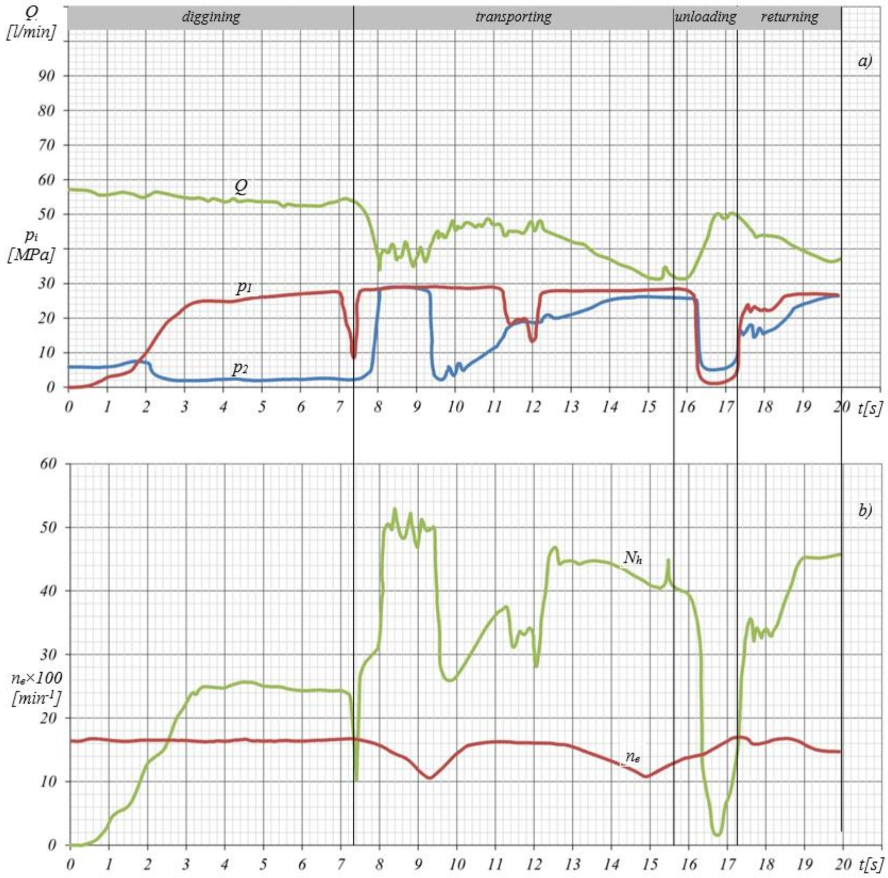

Fig. 3 Parameters of the drive system of a hydraulic excavator with fixed displacement hydraulic pumps: a) changes in pressures p_1 and p_2, and the flow rate Q of the hydraulic pumps b) changes in hydraulic power N_h and the rotational speed n_{en} of the diesel engine

If the resistances cause maximum pressures in the system, it leads to overloading of the drive motor (drop in revolutions), making the operation of the excavator more complex, as the operator must monitor the engine's performance with their senses and select appropriate working movements to prevent motor overload. Since the resistances are variable and the system flow is approximately constant (fig. 3a), it is not always possible to fully utilize the motor power and synchronize the speeds of the drive mechanisms with such a drive system.

In the drive system of an excavator with a dual hydraulic pump with collective regulation based on the criterion of constant hydraulic power and an ideal hyperbolic characteristic regulator, there is a drop in flow at the beginning of the operational task when working pressures increase (fig. 4a). This leads to a corresponding increase in engine power (fig. 4b). When one hydraulic pump is relieved, the engine power is sufficiently utilized at the maximum load of the other hydraulic pump [23].

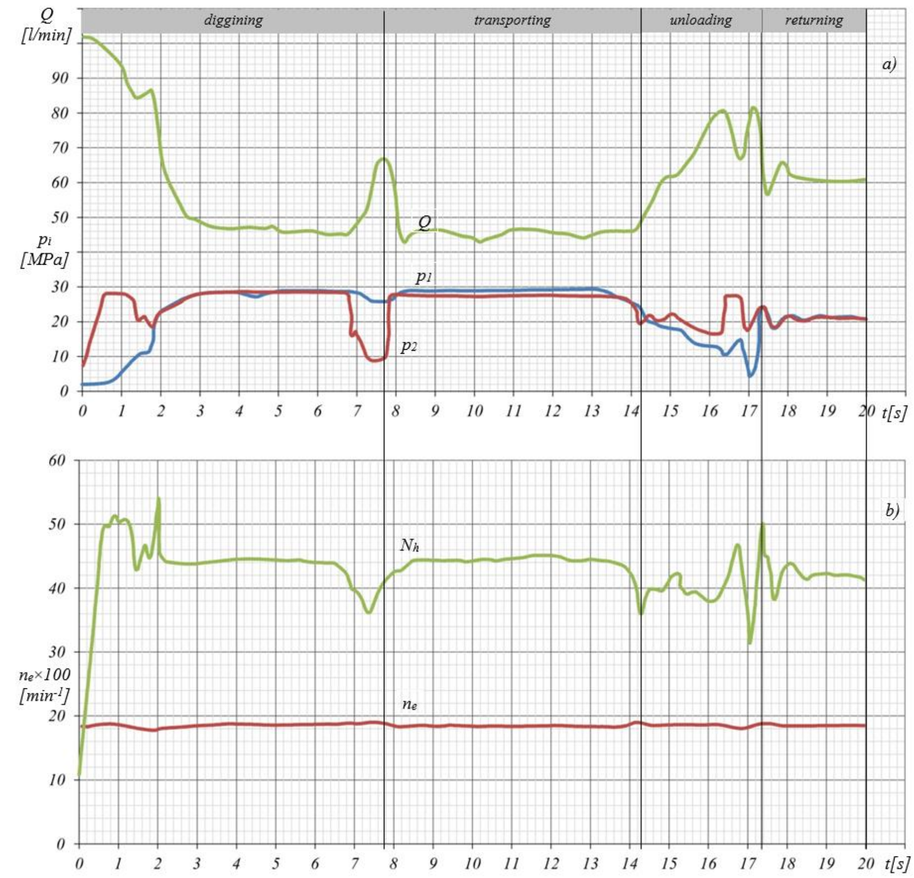

Fig. 4 Parameters of the drive system of a hydraulic excavator with hydraulic pumps of variable specific flow regulated by the criterion of constant hydraulic power a) changes in pressures p_1 and p_2, and the flow rate Q of the hydraulic pumps b) changes in hydraulic power N_h and the rotational speed n_{en} of the diesel engine

An increase in flow rate, i.e., the speed of the drive mechanisms, occurs when the load is reduced within the regulation interval of the hydraulic pump, with pressure remaining constant. The principle of the hydraulic pump regulation becomes even more pronounced during multiple work movements, that is, while performing a complete operational task. The movement resistances are not such that they cause maximum pressure, but they fall within the regulation range of the hydraulic pumps. Since the flow rates of both hydraulic pumps are identical while the pressures p_1 and p_2 are generally different, the power received by each pump will vary. The engine does not become overloaded at any point during the operational task. The brief occurrence of a power surge above normal levels is due to the rapid change in load and the inability of the flow regulator to react to relatively fast signals.

5. CONCLUSION

The use of hydraulic pumps with integrated power regulation and an ideal hyperbolic characteristic regulator in a hydraulic crawler excavator's drive system is examined in this study. Pressure and flow in the hydraulic pump pressure lines, as well as other characteristics of the hydrostatic drive mechanism, were measured during tests on the excavator. The study shown that using a combined power regulator to regulate the hydraulic pump according to the constant hydraulic power criterion enables the maintenance of constant hydraulic power even under changing load conditions, thereby optimizing engine power usage. This rule guarantees that the excavator operates efficiently throughout all duties, including excavating, moving, unloading materials, and putting the rotating platform back in its starting cycle position. The engine overload is effectively prevented by the regulation mechanism. By effectively preventing the engine overload, the regulating system enables hydraulic excavators to adapt to a variety of operating situations. The occurrence of short-term power increases at certain moments is a result of rapid load changes, but it does not compromise the overall system performance. The conducted analysis highlights the importance of the proper hydropump regulation to achieve efficiency and machine longevity.

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