MODELING THE OPERATIONAL PROCESSES OF CIVIL ENGINEERING MACHINERY EQUIPPED WITH POWER-SPLIT CVT

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Abstract - Improving the productivity and energy efficiency of earthmoving machines is one of the key directions in the development of modern construction and engineering equipment, particularly under conditions requiring large-scale earthworks, limited energy resources, and stringent reliability requirements. The application of power-split transmission systems is becoming increasingly relevant because they provide continuously variable speed control, improved traction performance, and rational power distribution between the mechanical and hydrostatic/electric branches. At the same time, the lack of mathematical models capable of comprehensively describing the interaction between the engine, transmission, working equipment, and the soil–tool interaction process limits the possibility of substantiating the optimal design parameters and operating modes of such machines. The aim of this study is to develop a mathematical model of an earthmoving machine equipped with a power-split transmission system, providing an integrated simulation of the interaction between the internal combustion engine (ICE), transmission, running gear, and working equipment during the trench excavation process. The proposed model is based on a system of interconnected equations describing the energy processes within the powertrain while accounting for variations in the load acting on the working attachment, the interaction between the propulsion system and the supporting surface, and the machine dynamics under real operating conditions. The practical significance of the obtained results lies in the possibility of applying the developed model to investigate the operational and technological performance of the machine, evaluate transmission component loading, predict techno-economic performance, and substantiate engineering design solutions for both the modernization of existing earthmoving machines and the development of advanced designs. In particular, simulation of a machine equipped with a hydro-mechanical transmission (HMCVT) demonstrated a rational distribution of power between the mechanical and hydrostatic branches, ensuring a stable tractive force at the working attachment. For the hybrid electromechanical transmission (eCVT), the simulation revealed a 34.4% reduction in the variation range of the effective engine torque and a 50% reduction in the crankshaft speed variation range, indicating a significant stabilization of the powertrain operating conditions. Furthermore, the concentration of operating points within a narrower region of the engine load map and their shift toward the engine speed range corresponding to the maximum torque create favorable conditions for improving the fuel economy and overall energy efficiency of the earthmoving machine.

Keywords: Earthmoving machine; Modeling; Power-split transmission; HMCVT; eCVT; Technological performance; Efficiency; operating cycle.

1. Introduction

The modern development of construction and engineering machinery is characterized by continuously increasing requirements for productivity, energy efficiency, and cross-country mobility when performing technological operations under challenging operating conditions.

One of the most promising approaches to improving the techno-economic performance of such machines is the application of power-split transmission systems, which provide rational power distribution between the mechanical branch and continuously variable power transmission branches, such as hydrostatic or electric drives.

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The use of these transmission systems extends the vehicle speed control range, improves traction performance, and enhances the efficiency of power utilization by the powertrain during technological operations.

At the same time, the design and improvement of construction and engineering machines equipped with power-split transmission systems require comprehensive investigations of their operating processes. The use of input data obtained from experimental studies of the trenching machine rotor penetration process makes it possible to refine the parameters of the mathematical model and improve its accuracy. The development of an adequate mathematical model enables the evaluation of the influence of transmission design parameters on vehicle performance, traction and speed characteristics, energy efficiency, and the operating behavior of the machine during technological operations.

Particular attention should be paid to investigating the operating processes of construction and engineering machines based on existing production models, since this approach makes it possible to assess the potential for transmission system modernization and to substantiate the most rational engineering solutions. Therefore, the development of a mathematical model describing the operation of a construction and engineering machine equipped with a power-split transmission system represents an important scientific and practical task. Its solution will contribute to improving machine operational efficiency and advancing methods for the design and optimization of next-generation transmission systems.

2. State of Modeling Earthmoving Machines Research

In recent years, research on the operating processes of earthmoving machines has increasingly focused on the application of mathematical modeling as the primary tool for substantiating design solutions and operating modes. This trend is driven by the high cost of full-scale experimental testing, the difficulty of reproducing identical soil conditions, and the need to investigate a wide range of design parameters. Consequently, modern mathematical models have gradually evolved from describing individual physical phenomena to integrated simulation of the interaction between the working attachment, the powertrain, the transmission system, and the soil environment.

A significant contribution to the systematization of current research trends in earthmoving machinery was made in [2], where the design of trenching machines was comprehensively reviewed using the PRISMA methodology. The authors identified improvements in energy efficiency, reduction of soil cutting resistance, integration of automatic control systems, and the transition toward model-based design as the principal directions of future development. At the same time, they emphasized that most existing studies investigate individual machine subsystems without comprehensively accounting for the interaction among the powertrain, transmission system, working equipment, and the soil environment.

A similar conclusion was reached by the authors of [3], who conducted a systematic review of automation technologies for earthmoving equipment. Their analysis showed that current research is primarily focused on specific tasks, including environmental perception, trajectory planning, work-cycle automation, and operational safety assessment. Despite the considerable progress achieved in digital modeling, universal mathematical models capable of simultaneously representing the energy processes within the powertrain, the power flow through the transmission system, and the variable loading generated by the working equipment remain largely unavailable.

Substantial progress in mathematical modeling has also been reported in studies [4, 5] devoted to specialized trenching machines. In particular, a comprehensive mathematical model was developed for an underwater chain trencher, incorporating soil cutting forces, traction characteristics of the carrier vehicle, drive power requirements, and the influence of working attachment design parameters on machine performance [5]. The conducted parametric study confirmed that mathematical modeling is an effective tool for optimizing machine design at the early stages of development.

One of the earliest comprehensive studies in this field is presented in [6], where a multidomain mathematical model of a wheel loader equipped with a hydro-mechanical power-split transmission was developed. The proposed model integrates mathematical models of the internal combustion engine, hydrostatic transmission, mechanical transmission components, vehicle dynamics, and the control system. Simulation results demonstrated that the application of the power-split transmission provides approximately 8% energy savings compared with a conventional hydrostatic transmission. However, the study was limited to the transport duty cycle of the wheel loader and did not account for the variable technological loading generated by the working attachment.

Further development of this research direction is presented in [7], where a mathematical model of the power flow within a HMCVT was developed and experimentally validated. The authors derived analytical relationships for determining torque, hydraulic fluid flow rate, and mechanical power losses under different operating conditions. The proposed model made it possible to evaluate the influence of transmission design parameters on its overall efficiency. Nevertheless, the transmission was considered as an isolated subsystem without integration into a mathematical model describing the technological operation of the machine.

A study of particular interest is reported in [8], in which a mathematical analysis of twenty-four hydrodynamic-mechanical power-split transmission configurations for heavy wheel loaders was carried out. Based on analytical models, the authors established relationships between the torque conversion ratio, transmission efficiency, and transmission ratio, providing recommendations for selecting the most efficient transmission configurations. However, the investigation focused exclusively on the kinematic and power characteristics of the transmission and did not consider the variable loading associated with the earthmoving process.

Another important research direction concerns the evaluation of energy losses in HMCVT. In particular, the study reported in [9] proposed an integrated approach for assessing energy losses by considering power circulation within the planetary power-summing gear set. The developed mathematical model enables the identification of rational transmission operating regions and the minimization of internal power losses. However, the proposed approach is primarily intended for transport operating conditions of traction vehicles and does not account for the specific operating characteristics of earthmoving equipment during technological operations. One of the most intensively studied areas is the modeling of hybrid hydraulic excavators. In particular, the authors of [10] proposed a novel powertrain architecture combining an internal combustion engine, a hydrostatic transmission, and an electric energy recovery system. Based on a comprehensive mathematical model and experimental validation, an energy management strategy was developed, resulting in a 9.44% reduction in total energy consumption and a 10.51% improvement in potential energy recovery efficiency. Nevertheless, the study primarily focused on the control strategy of the hybrid powertrain, whereas the influence of the variable technological load generated by the interaction between the working attachment and the soil was not comprehensively investigated. A similar approach was implemented in [11], where a mathematical model of an eCVT for a hybrid excavator was proposed. Particular attention was paid to optimizing the operating points of the internal combustion engine and implementing a boom potential energy recovery system. The simulation results confirmed the possibility of significantly reducing fuel consumption by maintaining the engine within its maximum efficiency operating region. However, the mathematical model was primarily intended for optimizing the control strategy and did not provide a comprehensive description of the interaction among the transmission system, the propulsion system, the working attachment, and the soil environment. Another promising research direction is the application of mathematical models for the synthesis of novel hybrid transmission systems for construction machinery. In [12], the authors proposed a power-split hybrid transmission for driving hydraulic working equipment and developed a mathematical model of the energy flows during a representative mini-excavator duty cycle. The simulation results demonstrated a substantial reduction in energy losses through the combined use of an electric drive and hydrostatic flow control. Nevertheless, the study was limited to the analysis of energy flows and did not investigate the influence of transmission parameters on the traction and speed characteristics of the machine.

The analysis indicates that current research on earthmoving machines is mainly concentrated in three areas: modeling the interaction between the working attachment and the soil (cutting forces, traction resistance, and energy consumption), power-split transmission systems, and integrated powertrains. However, most existing mathematical models describe only individual machine subsystems, focusing either on soil-tool interaction, transport operating conditions, or fuel economy. A unified mathematical model capable of simultaneously accounting for the internal combustion engine, the power-split transmission, the propulsion system, and the variable loading occurring during trench excavation has not yet been developed.

3. Materials and Methods

Developing a mathematical model of the motion of a construction machine performing the operational task of excavating trenches or pits requires the researcher to take into account a complex set of interrelated processes, among which the key factors are the generation of resistance forces by the working body during the disruption and displacement of soil, the transmission of power via the power drive and transmission, the interaction of the drive with the supporting surface, and changes in the machine's kinematic, force and energy parameters during the performance of the operational task. This formulation of the problem requires the establishment of interrelationships between the machine's energy, kinematic and force parameters, the characteristics of the soil medium, the operating modes of the working equipment and the performance indicators of the transmission system, thereby ensuring an adequate description of the processes of motion and the execution of the operational task within a single mathematical framework.

The description of an earthmoving machine's operating process must take into account both linear and non-linear relationships that characterise the interaction between the power unit, the transmission, the undercarriage and the working equipment. This approach makes it possible to replicate the actual operating conditions of the machine, under which the processes of machine movement, soil disruption and energy transfer to the working tool occur simultaneously. Since the aim of this work is to develop a mathematical model of an earth-moving machine's operation that takes into account the various components of its functioning, it is appropriate, for the sake of simplifying the model, to use a system of equations in a quasi-dynamic state, which describes the interrelationships between the power, kinematic and energy parameters of the machine, taking into account the influence of external and internal disturbances.

At the same time, modeling the operational processes of an earthmoving machine involves a number of specific features:

– the system's dynamics depend significantly on the variable digging resistance, the magnitude of which is determined by the physical and mechanical properties of the soil, the geometric parameters of the working body, and the operating modes during the performance of the operational task;

– the interaction of the working equipment with the soil results in variable loads on the transmission and power unit, which affects the delivery of tractive effort and the machine's energy efficiency;

– the non-linear nature of the interaction between the tractor and the supporting surface causes changes in the coefficients of adhesion, wheel slip and rolling resistance, depending on the soil condition and the machine's operating mode;

– changes in mass and the position of the centre of mass, resulting from the working body becoming filled with soil or the displacement of soil during operation, affect the distribution of loads between the supporting elements and the machine's stability characteristics;

– during the performance of operational tasks, inertial loads arise due to changes in the speed of the machine and the working equipment, which can significantly affect the dynamic operating modes of the transmission system.

3.1. Modeling of a Internal Combustion Engine

When modeling the operation of an internal combustion engine (ICE), simplified approaches are often used, allowing one to focus on its external characteristics without a detailed description of the thermodynamic processes taking place within the cylinders. In such cases, the engine is regarded as a source of mechanical energy with specified speed and load characteristics, whilst the effect of instantaneous fluctuations in torque on the crankshaft is considered negligible and is not taken into account.

However, the actual value of the torque developed by the engine varies throughout the operating cycle. This is due to the periodic nature of the combustion processes of the fuel-air mixture, changes in the pressure of the working fluid within the cylinders, and the inertial effects of the moving components of the crank-connecting rod and valve train mechanisms. As a result, torsional oscillations occur at the engine's output shaft, which can be expressed as the sum of the average torque value and variable components of a periodic nature.

The assumptions made during the development of the model make it possible to use the equation describing the rotational dynamics of an ICE crankshaft, which has been widely applied in studies [13, 14] devoted to the mathematical description of ICE operation, taking into account the inertial properties of rotating masses and the degree of engine loading.

$$J_e \cdot \frac{d\omega_e}{dt} = \left(\mathrm{M}_{\mathrm{normz}} + \frac{1 - \dfrac{\omega_e}{\omega_{\mathrm{nom}}}}{k_x - 1} \right) \cdot M_{\mathrm{nom}} - M_D, \tag{1}$$

where J_e is the moment of inertia; $d\omega_e/dt$ is the angular acceleration, characterizes the torque required to change the angular speed of the crankshaft; ω_{nom} is nominal angular speed of the crankshaft; M_{normz} is normalized torque; M_{nom} is nominal torque on the crankshaft; k_x is coefficient defining the slope of the governor branch of the external speed characteristic; M_D is resistive torque accounting for the load from the transmission, auxiliary units, and friction losses.

3.2. Modeling of Power-Split Transmissions

The transmission is represented as an equivalent torsional vibration circuit with two driven axes, corresponding to the front and rear axle drives. Each branch of the model contains summarised moments of inertia, stiffness and damping characteristics, whilst its output parameters are the torque, angular velocity and power transmitted to the respective wheel drives. This representation makes it possible to determine the traction forces at the wheels, assess the power distribution between the axles and automatically calculate the parameters of the interaction between the drive units and the ground, depending on the vehicle's operating mode.

Unlike the traditional approach, where some parameters are attributed to the internal combustion engine and others to the wheel drive, in this study all reduced parameters are attributed to the ICE shaft. This allows a single coordinate system to be used to describe kinematic and force processes, simplifies the structure of the mathematical model, and ensures a correct comparison of the energy and traction characteristics of different design variants of power-split CVT (Fig. 1, 2).

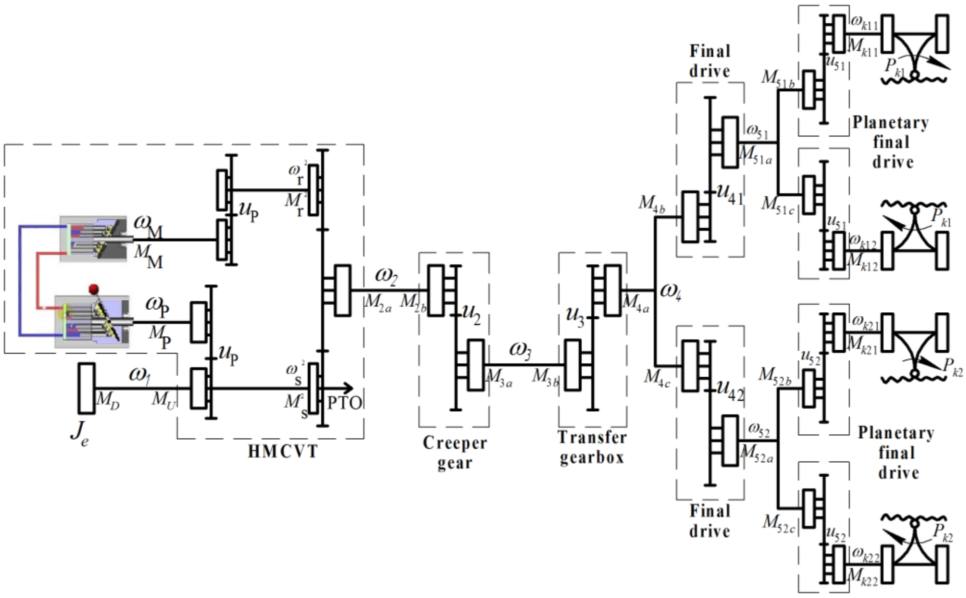


Figure 1: Kinematic scheme of an HMCVT [15]

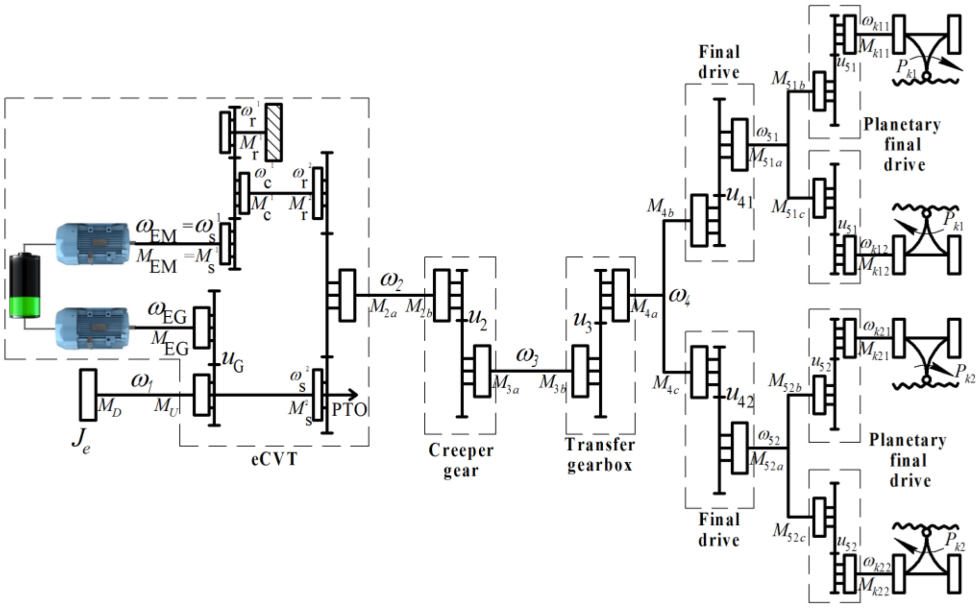


Figure 2: Kinematic scheme of an eCVT [16]

Mathematical modeling of the operation of dual-flow CVT requires the development of a unified approach to describing the processes of power transmission and conversion, regardless of the physical nature of the power drive. Despite the design differences between hydrostatic and electromechanical systems, both types of transmission implement the same principle of power flow distribution between the mechanical and continuously variable branches, which allows for the use of a unified mathematical model structure.

The kinematics of the hydraulic link is based on the following equations

$$-e_P \cdot q_P \cdot \omega_P + q_M \cdot \omega_M = \frac{K_y \cdot \Delta P \cdot \left(2 + C_y\right)}{\mu}\left(\left|\omega_P\right| + \left|\omega_M\right|\right), \qquad (2)$$

where e_P is the relative control ratio of the hydraulic pump (as the hydraulic motor is unregulated); ω_P, ω_M are angular velocity on the shafts of hydraulic machines; K_y is leakage coefficient of hydraulic machines; C_y is proportionality coefficient; ΔP is operating pressure drop in the hydraulic circuit; μ is dynamic viscosity coefficient; $q_{P,M}$ are maximum performance of hydraulic machinery.

The equations describing the power section of the hydraulic branch are as follows

$$M_P - e_P \cdot q_P \cdot \Delta P = -\Delta M_P \cdot \mathrm{sign}\left(\omega_P\right); \qquad (3)$$

$$M_M + q_M \cdot \Delta P = -\Delta M_M \cdot \mathrm{sign}\left(\omega_M\right), \qquad (4)$$

where $M_{P,M}$ are torque on the links of hydraulic machinery; $\Delta M_{P,M}$ are torque losses in hydraulic machines.

$$\Delta M_P = q_P \cdot \left[\begin{array}{l} K_1 \cdot |\omega_P| \cdot \left(1 + K_2 \cdot e_P^2\right) + \\ + \dfrac{K_5 \cdot \left(1 + K_4 \cdot |e_P|\right)}{\left(1 + K_3 \cdot |\omega_P| \cdot \sqrt[3]{2 \cdot \pi \cdot q_P}\right)} \cdot \Delta P + \\ + \dfrac{K_8 \cdot \left(1 + K_7 \cdot |e_P|\right)}{\left(1 + K_6 \cdot |\omega_P| \cdot \sqrt[3]{2 \cdot \pi \cdot q_P}\right)} \end{array} \right]; \quad (5)$$

$$\Delta M_M = q_M \cdot \left[\begin{array}{l} K_1 \cdot |\omega_M| \cdot \left(1 + K_2 \cdot e_M^2\right) + \\ + \dfrac{K_5 \cdot \left(1 + K_4\right)}{\left(1 + K_3 \cdot |\omega_M| \cdot \sqrt[3]{2 \cdot \pi \cdot q_M}\right)} \cdot \Delta P + \\ + \dfrac{K_8 \cdot \left(1 + K_7\right)}{\left(1 + K_6 \cdot |\omega_M| \cdot \sqrt[3]{2 \cdot \pi \cdot q_M}\right)} \end{array} \right], \quad (6)$$

where $K_{1\text{-}8}$ are hydromechanical loss coefficients determined by experimental studies.

A mathematical description of synchronous electric machines with permanent magnets has been carried out at the macro level in accordance with the control-oriented approach [17], which is widely used in the modelling of vehicle power systems. Unlike models based on the Park-Clark equations, in this case the electric motor is regarded as a controlled actuator that generates the required electromagnetic torque as specified by the transmission control system. This approach allows us to focus on investigating the processes of power flow distribution and the interaction of transmission components, significantly reducing the computational complexity of the model without compromising its accuracy when analysing traction and energy characteristics.

In the case of a single traction electric motor, the equation takes the form

$$M_{EG} = \frac{M_{EM} \cdot \omega_{EM}}{\omega_{EG} \cdot \eta_{EG} \cdot \eta_{inv} \cdot \eta_{EM}}, \quad (7)$$

where M_{EM} is the required torque on the rotor of an electric motor; ω_{EM}, ω_{EG} are angular velocities on the shafts of the electric motor and generator; η_{EG} is generator efficiency ($\eta_{EG} = f(M_{EG};\ \omega_{EG})$); η_{inv} is the efficiency of an inverter, which indicates the proportion of the input electrical power that is transferred to the converter's output, taking into account internal energy losses; η_{EM} is motor efficiency ($\eta_{EG} = f(M_{EM};\ \omega_{EM})$).

Thus, the generator torque is determined not directly by the torque of the traction motor, but via the balance between mechanical and electrical power in the electromechanical branch of the transmission.

3.3. Modeling of the Operation of Chain-driven Machinery

The steady-state operating process of an earthmoving machine (Fig. 3) with an active working body, in which all actuators are mechanically driven, can be described by a mathematical model for estimating the traction characteristics of a mobile machine, based on the solution of the following system of differential equations:

$$\begin{cases} m \cdot \ddot{X} + W_x = 2\left(P_{o1} + P_{o2}\right); \\ m \cdot \left(\ddot{Z} + g\right) + W_z = 2\left(G_{k1} + G_{k2}\right); \\ \dfrac{J_o \cdot \ddot{\varphi}_o}{2} + G_{k1}\left(X_{o1} - X\right) + G_{k2}\left(X_{o2} - X\right) = \\ = \dfrac{W_z}{2}\left(X_{o3} - X\right) - P_{o1}\left(Z_{o1} - Z\right) + \\ + P_{o2}\left(Z_{o2} - Z\right) + \dfrac{W_x}{2}\left(Z_{o3} - Z\right), \end{cases} \quad (8)$$

where X, Z, φ_o are generalised coordinates; P_{o1}, P_{o2} are forces that propel the frame of the earthmoving machine forwards; G_{k1}, G_{k2} are radial loads on tyres [18, 19]; W_x, W_z are horizontal and vertical components of the pulling force on the hook; x_{o1}, x_{o2}, x_{o3}, z_{o1}, z_{o2}, z_{o3} are horizontal and vertical coordinates of the tractor frame points in the selected reference system.

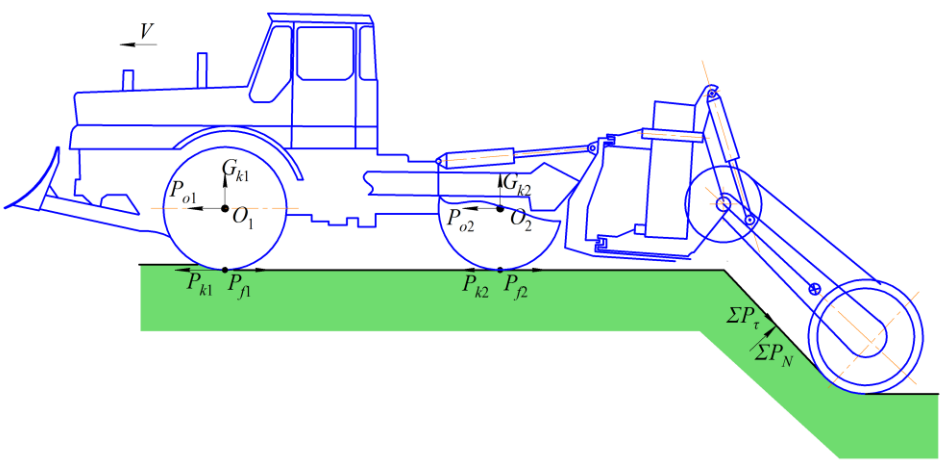


Figure 3: Calculation scheme of engineering machinery equipped

The horizontal and vertical components of the forces acting on the earthmoving machine whilst excavating a trench are as follows

$$W_x = \left(\sum_{i=1}^{14} P_N + \sum_{i=1}^{14} P_\tau \right) \cos 45^\circ ; \qquad (9)$$

$$W_z = \left(\sum_{i=1}^{14} P_N - \sum_{i=1}^{14} P_\tau \right) \cos 45^\circ , \qquad (10)$$

where P_N is resistance to the penetration of the tines into the soil; P_τ is cutting force.

It should be noted that the chain working unit consists of three rows of bushing-and-roller chains with teeth attached to them (Fig. 3), which act as cutting elements. The teeth are arranged in such a way that each subsequent tooth comes into action when the previous one exits the face (with the exception of the centre and side teeth). There are twice as many centre and side teeth: the centre teeth ensure stable operation of the chain in the face plane, whilst the side teeth serve to reduce the load on each tooth.

The resultant force consists of the soil cutting resistance, the resistance to tooth penetration into the soil, and the friction resistance of the tooth against the face. The formula for determining soil cutting forces is as follows:

$$P_\tau = 0.9 \cdot C \cdot h \left(1 + 0.55 \cdot n \cdot B\right) \left(1 - \frac{90^\circ - \alpha}{150^\circ}\right), \qquad (11)$$

where C is number of impacts of a dynamic density meter with a 1 cm^2 tip; h is cutting depth; n is number of teeth in a row across the working chain; B is width of the tooth cutting profile; α is tooth cutting angle.

The resistance to the teeth penetrating the soil is determined as follows

$$P_\tau = 0.875 \cdot n \cdot K_n , \qquad (12)$$

where K_n is specific resistance under static compression.

Thus, a mathematical model of the operation of an earthmoving machine in a quasi-dynamic space has been developed, which describes the interaction between the ICE, the transmission, the undercarriage and the chain-driven working body. The proposed approach makes it possible to investigate the steady-state operating modes of the machine, taking into account the resistance to the penetration of the teeth into the ground, cutting forces and the load distribution between the elements of the power train.

3.4. Identification of the Load Characteristic

Soils on which the tests were carried out: plots of land with Category II soils (chernozem, loam). The tests were carried out during the winter and spring months at air temperatures ranging from −4°C to +6°C, wind speeds of 2 to 5 m/s, relative humidity of 70% to 95% and atmospheric pressure of 748 to 762 mm Hg. The studies were carried out during daylight hours in the absence of precipitation. The work was carried out on soil in a thawed-frozen state with a temperature in the soil mass ranging from −2°C to +2°C, corresponding to the transition period from a frozen to a thawed state. According to the results of a preliminary survey, the depth of soil freezing was 0.10 - 0.25 m, which ensured the presence of a frozen surface layer and plastic lower horizons, characteristic of the operating conditions for earthmoving machinery during the cold season.

Experimental studies of the digging process show that the load on the working body has a complex, non-stationary structure. Its magnitude varies depending on the physical and mechanical properties of the soil, the cutting depth, the machine's travel speed, the geometry of the working body, and the mode of interaction between the cutting elements and the soil mass. Under real-world conditions, the load takes the form of a sequence of non-uniform pulses superimposed on a varying average component, reflecting both transient and steady-state operating modes.

The load characteristics are identified on the basis of experimental oscillograms obtained during field tests (Fig. 4). To this end, the time-domain realisations of the force components are measured, followed by pre-processing, which includes noise filtering, trend removal, signal normalisation and synchronisation with the kinematic parameters of the working process. At this stage, the main statistical indicators are determined: the mean value, standard deviation, amplitude limits, coefficient of variation and intervals of the most probable load values.

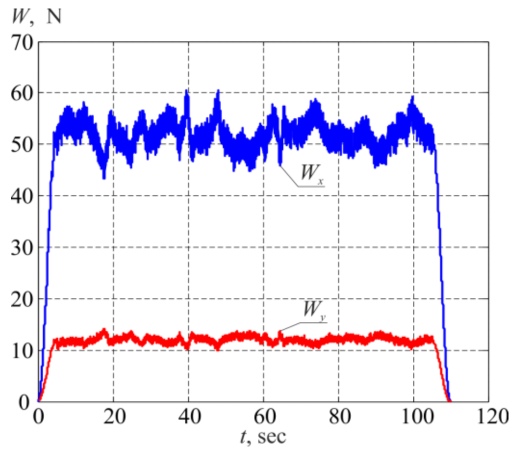


Figure 4: Load characteristic of an earthmoving machine

Further analysis of the experimental data makes it possible to establish the temporal structure of the load and to identify characteristic phases of the working cycle. In particular, for earth-moving machinery, the typical phases are the penetration of the working tool into the ground, the main cutting phase, the movement of soil, and the completion of the cycle. Each of these stages has its own level of force load and distinct vibration intensity. It is for this reason that the identification of load characteristics must take into account not only the average values of the forces, but also their variation within the individual phases of the operational process.

4. Results

Before proceeding to the modelling of the operational processes of a civil engineering machine with power-split transmissions, it should be noted that the machine is equipped with a 175 hp diesel ICE, the variation in the effective efficiency of which is shown in Fig. 5. For the operation of the HMCVT, GST-112 hydraulic units (Hydrosila TD Ltd) were selected, specifically: a variable-displacement hydraulic pump and a fixed-displacement hydraulic motor. Bosch SMG230/132 electric motors were selected for the operation of the eCVT [16]. Fig. 6 shows the distribution of operating points for varying the effective power of the ICE during the simulation of the earth-moving machine's operation.

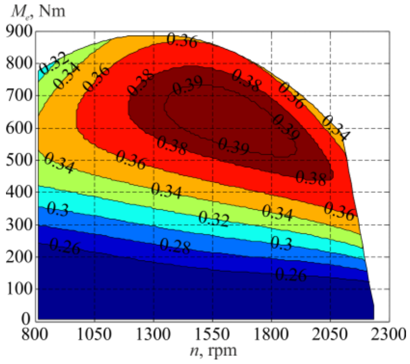
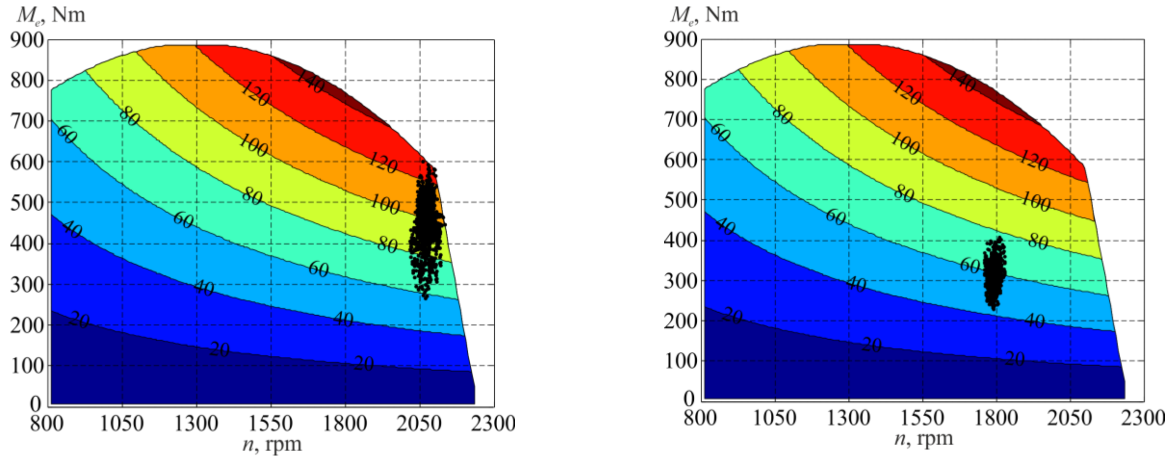


Figure 5: Change in effective efficiency of a 175 hp diesel ICE

Comparing the results for the effective power of the internal combustion engine in Fig. 6 (a, b), it should be noted that when using the proposed eCVT, the operating points shift towards lower angular velocities and reduced torque. The same process is observed in [16] when a hybrid transmission is implemented in a wheeled tractor. This condition is desirable from the point of view of fuel efficiency; however, under these conditions, the internal combustion engine does not operate at its optimum load, i.e. it is underloaded. Fig. 5 is constructed according to the spatial principle [20, 21] for the purpose of greater clarity of the obtained results.



a b

Figure 6: Change in the distribution of operating points of the effective power of the ICE during the simulation of the load cycle of an earthmoving machine with HMCVT (a) and eCVT(b)

5. Discussion

An analysis of the operating modes of the internal combustion engine during the implementation of the synthesised load cycle showed that, for an earthmoving machine, the power unit typically operates at a virtually constant crankshaft speed. During the digging process, the engine's speed governor maintains the rotational speed at a level close to the rated value (around 2100 rpm), so its instantaneous deviations do not exceed 10 - 15 per cent even in the presence of significant random changes in working resistance forces. Under such conditions, the determining factor for changes in the engine's operating mode is not the rotational speed, but the magnitude of the effective torque and the corresponding effective power.

An analysis of the distribution of operating points of an internal combustion engine along the load characteristic curve has made it possible to assess the influence of the transmission configuration on the operating modes of the power unit during the execution of a simulated load cycle for an earth-moving machine. It has been established that when using an HMCVT, the operating points occupy a significantly larger area of the engine map, indicating a substantial change in its operating modes under random power loads. During the digging process, the effective torque varies approximately from 280 to 600 Nm, whilst the crankshaft speed ranges from 1980 to 2160 rpm. This distribution pattern indicates that load changes are transmitted directly from the working tool to the engine, as a result of which the latter operates across a wide range of loads and rotational speeds.

For the hybrid eCVT, the distribution of operating points changes significantly. The range of effective torque is reduced to 220 - 430 Nm, whilst the operating speeds of the internal combustion engine are concentrated within the range of 1,750 - 1,840 rpm. As a result, the area of the operating point distribution is significantly reduced, indicating a more stable operating mode for the internal combustion engine.

A comparative analysis shows that the use of eCVT reduces the range of effective torque by approximately 56 per cent (from 320 to 210 Nm) and the range of engine speed by approximately 50 per cent (from 180 to 90 rpm). At the same time, there is a shift in the engine's operating range towards lower rotational speeds, which corresponds to operating modes with higher effective efficiency and lower specific fuel consumption. This result indicates that the electromechanical component of the transmission compensates for transient load changes, enabling the engine to operate within a narrower load range without the need to maintain a high rotational speed.

The resulting effect is due to the redistribution of power flows between the internal combustion engine, the electric motor and the energy storage device. Whilst in an HMCVT virtually all instantaneous changes in driving resistance are directly absorbed by the engine, in a hybrid system short-term peak loads are compensated for by the electric motor. As a result, the internal combustion engine operates predominantly under steady-state conditions, whilst the electric motor ensures the balancing of energy flows during sudden changes in load.

6. Conclusions

The proposed mathematical model enables the determination of instantaneous values for torque, rotational speed, effective power and specific fuel consumption of an internal combustion engine, as well as the operating parameters of the electric motor and battery, and the energy flows between the individual components of the power train. This enables a comprehensive analysis of the impact of the transmission's structure on fuel economy, energy efficiency and the operational dynamics of the earthmoving machine under real-world operating conditions.

It has been established that the use of a hybrid eCVT reduces the range of variation in the engine's effective torque from 320 to 210 Nm (by 34.4 per cent) and the range of crankshaft rotational speed from 180 to 90 rpm (by 50 per cent), which indicates a stabilisation of the power unit's operating modes. The concentration of operating points within a narrower region of the load characteristic curve and their shift to the 1,750 - 1,840 rpm range create the conditions for improving the fuel economy and energy efficiency of the earthmoving machine.

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