MODELING OF TRANSITION PROCESSES AND FUEL CONSUMPTION BY MACHINE-TRACTOR UNIT USING BIOFUEL
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МОДЕЛЮВАННЯ ПЕРЕХІДНИХ ПРОЦЕСІВ ТА ВИТРАТ ПАЛИВА МАШИНО-ТРАКТОРНИМ АГРЕГАТОМ ПРИ ЗАСТОСУВАННІ ДИЗЕЛЬНОГО БІОПАЛИВА

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ABSTRACT
It was developed the mathematical model of Machine-tractor unit (MTU) work dynamics based on the analysis of the forces acting at ploughing works. The model reflects the relationship between the operational and structural parameters of the MTU and the properties of the agro-technological environment and the type of fuel that is used. Modeling allows selecting the rational composition of the MTU and predicting the effective performance of its operation modes, depending on the parameters of the agro-technological environment and the type of fuel.

РЕЗЮМЕ
Розроблено математичну модель динаміки роботи МТА на основі аналізу сил, діючих під час виконання технологічної операції оранки. Модель відображає взаємозв'язок між експлуатаційними й конструктивними параметрами МТА та властивостями агротехнологічного середовища й типом палива, що застосовується. Моделювання дозволяє виконувати вибір раціонального складу МТА та прогнозувати ефективні показники режимів його роботи в залежності від параметрів агротехнологічного середовища та типу палива.

INTRODUCTION
Machine-tractor unit (MTU) must perform technological operations in compliance with the relevant agro-technological requirements and provide high performance with minimal fuel costs. However, these indicators significantly depend on the operating conditions, physical and mechanical properties of the environment, design parameters, operation modes of the MTU, and the type of fuel. Thus, they can vary widely. Forecasting changes in the parameters of the MTU and the calculation of optimal performance and operation modes, depending on the operating conditions is an urgent need for modern agricultural production.

To calculate the parameters of the MTU, it was created a significant number of mathematical models (*Tiwari V.K., Pandey K.P. Pranav P.K., 2010*; *Battiato A., Diserens E., 2017)*. The necessity of using a system approach with application of analytical methods for modeling the MTU parameters (*Freitag D.R., 1985; Yong R.N., 1976*) is shown. It is also mentioned the lack of accuracy of the results when applying the known semi-empirical (*Bekker M.G., 1956; Wong J., 2001*) and empirical *(Brixius W.W., 1987; Wismer R.D., Luth H.J., 1973)* dependences.

The empirical dependence for the calculation of the MTU traction power, given in *(Brixius W.W., 1987)*, has been improved by introducing the characteristics of the agro-technological environment (*Tiwari V.K., Pandey K.P., Pranav P.K., 2010)*. The accuracy of the results of this model is limited by the operating conditions of the wheels under which this dependence is obtained.

In the study done by *Battiato A.& Diserens E., (2017)*, the power analysis of the interaction of the drive wheel with the soil was performed and a mathematical model for calculating the traction power of the power unit was developed. The resulting model takes into account the parameters of the drive wheels and the soil and allows simulating the traction power, which can be developed by power unit. The disadvantage of the developed model is the lack of possibility of taking into account the variable modes of operation of the engine and the variable traction resistance of the working unit.

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To perform the simulation of the MTU performance indicators, a generalized model has been developed that relates the ballast weight, tire pressure, transmission characteristics, engine speed, and workload to fuel consumption indicators *(Lee J.W., Kim J.S., Kim K.U., 2015)*. The generalized model is formed on the basis of models of the engine, transmission, fuel consumption and traction power. The empirical dependence given in *(OECD Code 2, 2010)* is used as a model of the engine and transmission. Fuel consumption modeling was performed using the nomogram of fuel consumption dependence on load *(Kim S.C., Kim K.U., Kim D.C., 2010)*. Traction power was determined by empirical dependence given in *(Lacour S., Burgun C., Perilhon C., Descombes G, Doyen V., 2014)*. Considering that the developed model is based on empirical dependences, the simulation results do not provide an opportunity to establish a relationship between the MTU parameters and its performance. It should also be noted that this model does not take into account the properties of the agro-technological environment, which have a direct impact on the effective performance of the MTU. In addition, the nomogram to determine the fuel consumption dependence on the operating modes of the engine and its load *(Kim S.C., Kim K.U., Kim D.C., 2010)* can be used only at known MTU load values.

In the work of *Previati G., Gobbi M. & Mastinu G., (2007)* the power analysis of the MTU work when performing the technological operations of agricultural production is provided. On this basis, a mathematical model is developed, which consists of several equations characterizing the work of the MTU. These equations establish the relationship between mechanical energy and fuel consumption. The use of such a model requires the use of experimental equations characterizing the MTU work. In addition, the mathematical model does not take into account the parameters of the agro-technological environment, which can vary widely.

The Lagrange equation *(Bulgakov V., Adamchuk V., Arak M. et al., 2016; Makharoblidze R., Lagvilvaval I., Basilashvili B., Khazhomia R., 2016)* with the use of known empirical and semi-empirical dependences was applied for the complex combination of tractor systems, working unit and agro-technological environment. This made it possible to link the MTU parameters with changes in energy costs in the system. However, since empirical and semi-empirical dependences describe the work of individual subsystems, their connection to the general system does not allow establishing general relationships characterizing the work of the MTU as a whole.

To assess the parameters of the MTU a mathematical model based on the second Newton's law is also developed *(Kolator B., Bialobrzewski I., 2011)*. The authors consider the MTU as an object with variable mass; its load is given in the form of variable masses, which are included or combined accordingly in the dynamic system. The obtained dynamic model on the basis of Newton's second law allows considering the change in the dynamic parameters of the system with a known change in the masses in the system. The use of such a model does not allow taking into account the changes in the properties of the agro-technological environment. That is why the use of this model for practical purposes is very difficult.

In studies of dynamic processes of tractor controllability depending on ground conditions, the second Newton's law is also applied in the formation of the dependence of the tractor longitudinal motion *(Kayacan E., Kayacan E., Ramon H., Saeys W, 2015)*. Forming this model, the authors decomposed the current acceleration relative to the selected coordinate system, which made it possible to determine the rotational forces during tractor movement. However, when forming the model, the authors neglected the formation of the tractor traction force and the forces that counteract the movement from the working unit. The results obtained by the authors are suitable for the evaluation of tractor control, but do not allow modeling the magnitude of the tractive effort in the MTU. In the work of *Liu Z., Bai X., Wang Z., Gao L. (2018)* to create a system of automatic speed control it was developed and implemented in Simulink the model representing the longitudinal dynamics of a tractor. The combination of mathematical models of modules characterizing the internal and external components of the tractor motion system is based on Newton's second law. This approach allowed obtaining a numerical solution of the general system with respect to a certain indicator, but does not reveal the essence of the interaction that occurs between the parameters characterizing the movement of the tractor.

A model in which the MTU is considered as a system of equilibrium of external forces and the sum of moments is also known *(Golub G., Chuba V., Kukharets S., 2017)*. On its basis, the dependence is obtained to determine the coefficient of overall efficiency of the tractor, speed, fuel consumption, torque on the drive shaft of the engine, and the angular velocity of the crankshaft. However, a significant drawback of this model is that the MTU is considered in static mode with a known traction load. This approach does not reveal the essence of interaction of various parameters of MTU and does not allow performing its modeling in dynamic mode.

The analysis of existing approaches and models showed the absence of a mathematical model that would reveal the essence of the interaction of various parameters of the MTU and provide sufficient accuracy for forecasting the MTU performance. The formation of a mathematical model of MTU dynamics taking into account the interaction with the agro-technological environment, and taking into account the type of fuel, will provide a solution suitable for modeling the MTU work. The model of the MTU motion dynamics should determine the relationship between the structural and operational parameters of the power plant, the working unit and the agro-technological environment, as well as the characteristics of the fuel that is used.

MATERIALS AND METHODS

The formation of a mathematical model of the MTU dynamics was carried out on the basis of the laws of mechanics, based on the power analysis of the MTU and taking into account the parameters of the agro-technological environment.

When performing experimental studies, it was used the MTU on the basis of the 4WD tractor Kyi-14102 (*Kyi – 14102)*. with the total weight of 39.1 kN and the engine power of 76.95 kW, equipped with the system of fuel consumption measurement, and the plough PRO-3 with a width of 1.05 m. The change in the width was simulated by a step-change in the number of the plough bodies employed during operation (Fig.1).

During the experimental studies, standard winter diesel fuel of oil origin and biofuel based on methyl esters of fatty acids obtained from rapeseed oil were used.

Fig. 1 - Type of the MTU used to study the effect of the plough width and fuel type on the performance of its operation

When performing theoretical calculations were taken the values of the tractor performance and agro-technical environment in accordance with those for which the experimental studies were carried out.

To check the adequacy of the obtained theoretical dependence, a comparison of experimental and theoretical data of the MTU working during the technological operation of ploughing was performed. To test the obtained theoretical model, experimental studies have been carried out to determine the effect of the width of the working unit on the power unit fuel consumption in the MTU.

To measure the fuel consumption, an additional tank was used, which was connected in parallel with the main fuel system of the engine (Fig. 2). Before using diesel biofuels, the MTU engine worked for 30 minutes to replace the diesel fuel residue in the fuel system.

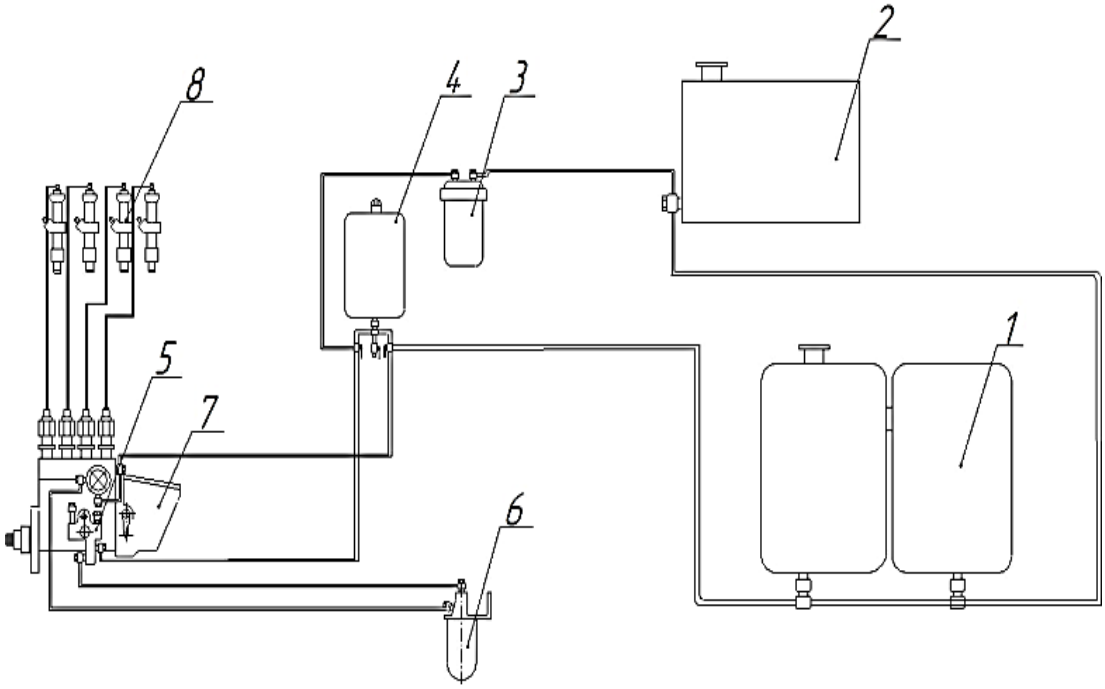

Fig. 2 - Scheme of connecting an additional tank to the fuel system of the engine
1 – tank for diesel fuel; 2 – tank for diesel biofuel; 3 – coarse filter; 4 – additional tank; 5 – suction pump; 6 – fine purification filter; 7 – high pressure fuel pump; 8 – nozzles

The prescribed volume of fuel was filled in the additional tank. The remained fuel was poured off after each experiment. The difference between the initial and final fuel volumes determined the amount of spent fuel when MTU passed of the experimental site.

RESULTS

Power unit in the construction of the MTU, depending on the operation that is performed, provides the creation of a traction force (to move and drive the working unit), or the transmission of the necessary energy (using the power take-off shaft (PTO). The chemical energy of the fuel is converted in the internal combustion engine into the translational motion of the pistons. The translational motion of the pistons by means of the engine crankshaft is converted into rotational one. The force of the gas pressure on the piston is converted into torque, which is transmitted by the transmission to the drive wheels and (PTO).

In this case, the dynamics of the MTU motion can be described on the basis of Newton's second law, which can be presented in the following form:

$$m_{MTU}\frac{dV}{dt} = F_T - F_{FR} - F_{AR} - F_{FM} \tag{1}$$

where:

$m_{MTU}=m_T+m_{WM}$ – the weight of the MTU in the construction of a tractor and a working machine, kg;

$\frac{dV}{dt}$ – linear acceleration of the MTU, m/sec^2;

V – movement speed of the MTU, m/sec;

dt – changing in the time of the MTU movement, sec;

F_T – tractor pull force, N;

F_{FR} – the force to overcome the rolling friction of the tractor wheels in the soil, N;

F_{AR} – the force of air resistance during tractor movement, N;

F_{FM} – the traction resistance force of the working machine, N.

The torque of the engine depends on the amount and calorific value of the fuel, and the effective efficiency of the internal combustion engine. Part of the engine torque is spent on overcoming the resistance of the transmission. When converting the engine torque into the pulling power, it occurs the input of the part of the torque for slipping of the driving wheels. Then the traction force can be determined using the following relationship *(Golub G., Chuba V., Kukharets S., 2017)*:

$$F_T = \frac{1-\delta_S}{r_{DT}}\left(\frac{S_{PL}l_{PL}\rho_F k_{PL} i}{2\pi}Q_F\left(\alpha\omega^2+\beta\omega+\gamma\right)k_{CREB} - \frac{M_{PTO}}{i_{TRPTO}\eta_{TRPTO}}\right)i_{TR}\eta_{TR} \tag{2}$$

where:

δ_S – slipping factor, rel. un.;

r_{DT} – radius of the drive wheel taking into account the deformation of the tire, m;

S_{PL} – the area of the plunger pair, m^2;

l_{PL} – active stroke of plunger, m;

ρ_F – fuel density, kg/m^3;

k_{PL} – the ratio of fuel supply by the fuel pump plunger;

i – number of fuel injections per engine rotation, rot^{-1};

Q_F – lower calorific value of fuel, kJ/kg;

ω – angular velocity of engine crankshaft, 1/sec;

α, β, γ – the coefficients of approximation of the dependence of the change in the effective efficiency of the engine on the change in the angular velocity of the engine crankshaft (external speed characteristics);

k_{CREB} – the reduction coefficient of the effectiveness of the bio-diesel use when compared to diesel fuel; rel. un.;

M_{PTO} – torque on power take-off shaft; N m;

i_{TRPTO} – transmission ratio from engine to power take-off shaft, un.;

η_{TRPTO} – coefficient of the efficiency of the power take-off shaft transmission, rel. un.;

i_{TR} – the gear ratio of the power unit drive transmission, rel. un.;

η_{TR} – coefficient of efficiency of the power unit drive transmission, rel. un.

Let us express the forces of resistance to movement with the help of well-known formulas characterizing the nature of the origin of resistance. The force to overcome the rolling friction of the tractor wheels in the soil:

$$F_{FR} = \frac{M_{FR}}{r_{DT}} = f m_T g \tag{3}$$

where: M_{FR} – the moment to overcome the friction of the tractor wheels rolling on the ground, N m;

f – the coefficient of rolling friction of the tractor wheels on the ground, rel. un.;

m_T – tractor weight, kg; g – acceleration of gravity, m/sec ^{2}.

The power to overcome the air resistance of the MTU:

$$F_{AR} = k_{AR} S_{FAD} V^2 \tag{4}$$

where: k_{AR} – air resistance coefficient, N sec^2/m^4;

S_{FAD} – area of the MTU drag, m^2.

Resistance, which is created by a working machine can be most fully characterized by a rational formula by P. Horiachkin *(Horyachkin V. P., 1940)*, describing the physical essence of the phenomenon of the emergence of agricultural implements resistance and is suitable for describing any tillage machine:

$$F_{FM} = P_1 + P_2 + P_3 = f^{/} m_{WM} g + kab + \theta ab V^2, \tag{5}$$

where: P_1 – the force arising under the weight of the machine and the action of friction forces when it is moving, N;

P_2 – the force expended on the deformation of the treated layer of soil during the useful work, N;

P_3 – the force arising from the interaction of the working surface and the particles of the tilled environment, as a result of which the latter are given acceleration and displacement, N;

$f^{/}$ – the total coefficient of friction, which includes the friction of the tool on the soil and the rolling friction of the support wheel of the plough, rel. un.;

m_{WM} – the mass of the working machine, kg;

k – specific resistance to soil deformation, N/m^2;

a – the width of the tilled layer, m;

b – the depth of the tilled layer, m;

θ – coefficient taking into account the ratio of the layer throw away rate and the plough speed, N sec^2/m^4.

Taking into account the traction force and resistance forces, expressing the speed of the MTU motion and acceleration through the angular velocity of the crankshaft, the expression (1) takes the following form:

$$\frac{(m_T + m_{WM}) r_{DT}^2 (1-\delta_S)}{i_{TR}} \frac{d\omega}{dt} =$$

$$= \left(\frac{S_{PL} l_{PL} \rho_F k_{PL} i Q_F (\alpha\omega^2 + \beta\omega + \gamma) k_{CREB}}{2\pi} - \frac{M_{PTO}}{i_{TRPTO} \eta_{TRPTO}} \right) (1-\delta_S) \eta_{TR} i_{TR} - \tag{6}$$

$$- r_{DT} f m_T g - \frac{k_{AR} S_{FAD} \omega^2 r_{DT}^3 (1-\delta_S)^2}{i_{TR}^2} - r_{DT} f' m_{WM} g - r_{DT} k ab - r_{DT} \theta ab \left(\frac{\omega}{i_{TR}} r_{DT} (1-\delta_S) \right)^2 .$$

By entering in (6) replacements:

$$A = \frac{(m_T + m_{WM}) r_{DT}^2 (1-\delta_S)}{i_{TR}};$$

$$G = \frac{S_{PL} l_{PL} \rho_F k_{PL} i Q_F k_{CREB}}{2\pi} (1-\delta_S) \eta_{TR} i_{TR};$$

$$C = \frac{k_{AR} S_{FAD} r_{DT}^3 (1-\delta_S)^2}{i_{TR}^2} + r_{DT} \theta ab \left(\frac{r_{DT}}{i_{TR}} (1-\delta_S) \right)^2 = \frac{(k_{AR} S_{FAD} + \theta ab) r_{DT}^3 (1-\delta_S)^2}{i_{TR}^2};$$

$$H = \frac{M_{PTO}}{i_{TRPTO} \eta_{TRPTO}} (1-\delta_S) \eta_{TR} i_{TR};$$

$$I = r_{DT} f m_T g + r_{DT} f' m_{WM} g + r_{DT} k ab = r_{DT} (f m_T g + f' m_{WM} g + k ab),$$

where:

A – component of the moment of the MTU inertia, kg m^2;

G – the energy of the fuel, based on the parameters of fuel supply, J;

C – effect of air drag and kinetic energy during the movement of the soil layer, N sec^2 m;

H – moment of resistance on the power take-off shaft, N m;

I – the sum of the moments of resistance of tractor moving, friction resistance at unit movement and resistance of soil layer deformation, N m.

The differential equation (6) takes the form:

$$A \frac{d\omega}{dt} = G(\alpha\omega^2 + \beta\omega + \gamma) - H - I - C\omega^2, \tag{7}$$

or

$$A \frac{d\omega}{dt} = G\alpha\omega^2 + G\beta\omega + G\gamma - H - I - C\omega^2 . \tag{8}$$

After introduction of replacements $P = \frac{G\alpha - C}{A}$; $L = \frac{G\beta}{A}$; $K = \frac{G\gamma - H - I}{A}$ and the corresponding permutations of equation (8), it takes the form:

$$\frac{d\omega}{P\omega^2 + L\omega + K} = dt \tag{9}$$

After integrating the differential equation (9), we obtain the equation of indefinite integrals:

$$\int \frac{d\omega}{P\omega^2 + L\omega + K} = \int dt \tag{10}$$

According to *Dwight H. B. (1966)*, the solution of the indefinite integral (10) is the equation:

$$\frac{1}{\sqrt{L^2 - 4PK}} \ln \left| \frac{2P\omega^2 + L - \sqrt{L^2 - 4PK}}{2P\omega^2 + L - \sqrt{L^2 - 4PK}} \right| = t \tag{11}$$

Substituting the limits of integration into equation (11), we obtain a definite integral:

$$\int_{\omega_I}^{\omega_T} \frac{d\omega}{P\omega^2 + L\omega + K} = \int_{t_I}^{t_T} dt \tag{12}$$

where:

ω_I – initial angular velocity of the engine crankshaft, rad/sec;

t_I – initial time value, rad/sec.;

ω_T – the final value of the engine crankshaft angular velocity, rad/sec.;

t_T – final time value, rad/sec.

The solution to the left-hand side of equation (12) according to the formula of Newton – Leibniz has the form:

$$\frac{1}{\sqrt{L^2-4PK}}\ln\left|\frac{2P\omega_T+L-\sqrt{L^2-4PK}}{2P\omega_T+L+\sqrt{L^2-4PK}}\right|-\frac{1}{\sqrt{L^2-4PK}}\ln\left|\frac{2P\omega_I+L-\sqrt{L^2-4PK}}{2P\omega_I+L+\sqrt{L^2-4PK}}\right|=t \quad (13)$$

where: t – time characterizing the duration of the process of changing the angular velocity from the initial to the final value, sec.

After performing the appropriate transfers, subtracting, getting rid the logarithms, making the necessary transformations with respect to the final angular velocity of the crankshaft ω_T and entering a replacement $J=\sqrt{L^2-4PK}$, we obtain the solution of the differential equation (6) in the following form:

$$\omega_T=\frac{1}{2P}\left(J\left(\frac{2P\omega_I+L+J\frac{\left(1-e^{tJ}\right)}{\left(1+e^{tJ}\right)}}{\left(2P\omega_I+L\right)\frac{\left(1-e^{tJ}\right)}{\left(1+e^{tJ}\right)}+J}\right)-L\right), \quad (14)$$

The resulting equation describes the dynamics of the engine crankshaft angular velocity when changing the external parameters characterizing the MTU work in the performance of technological operations and characteristics of the fuel used.

On the basis of the obtained mathematical model of dynamics (14) the modeling of changes in the operating parameters of the MTU using diesel fuel and diesel biofuels is provided. For example, the theoretical modeling of MTU dynamics was carried out for the conditions of the technological operation of ploughing at the values of the parameters given in the table. 1. Characteristics of fuel and soil properties were measured under both laboratory and field conditions. When performing research of the MTU work it was simulated a sudden increase in the resistance of the agro-technological environment and increase in the fuel supply to achieve the initial speed. As a result of theoretical modeling, are obtained the dependences of the change in the angular velocity of the engine crankshaft, the speed of motion of the MTU (Fig. 3) and fuel consumption (Fig. 4) depending on the resistance of agro-technological environment, and fuel supply for different types of fuel.

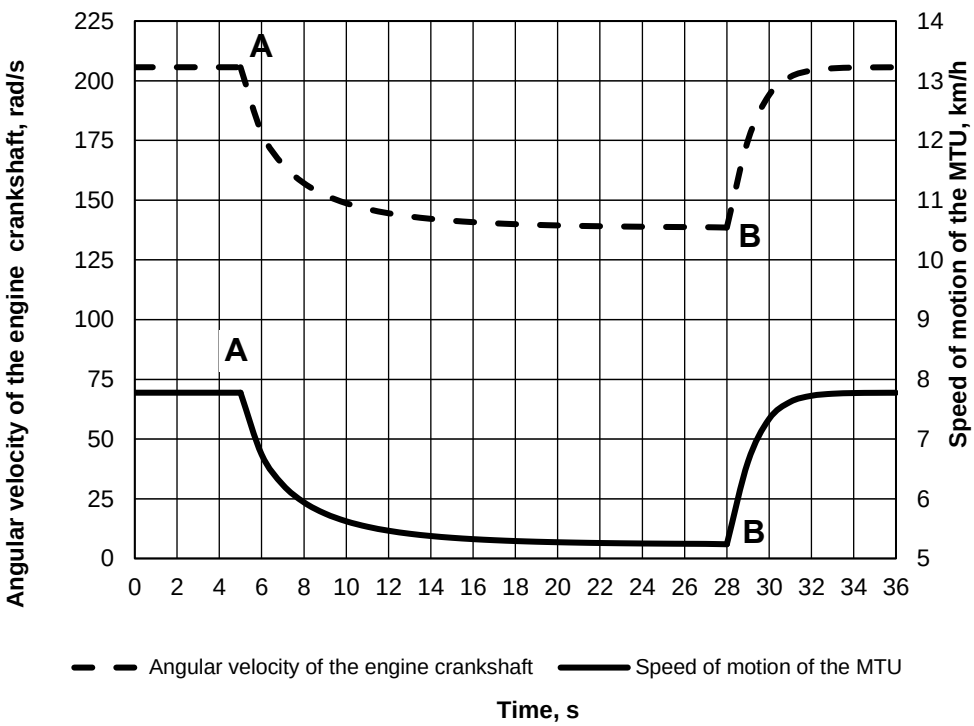

Fig. 3 - Dynamics of high-speed characteristics of the engine and MTU after changing the load and the subsequent change in fuel supply

Table 1

The value of the MTU parameters and agro-technological environment

Indicator		Un.	Symbol	Value
Power unit parameters				
Tractor weight (Kyi -14102)		kg	m_T	3910
The radius of the drive wheel taking into account the tire deformation		m	r_{DT}	0.75
High pressure pump plunger steam area		m^2	S_{PL}	0.00005672
Active stroke of the plunger of the high-pressure pump when working on diesel fuel	initial	m	l_{PL}	0.002230064
	final			0.002535543
Active stroke of the plunger of the high-pressure pump when working on diesel fuel	initial	m	l_{PL}	0.002619029
	final			0.002977789
The ratio of fuel injection by the plunger of the fuel high-pressure pump		rel. un.	k_{PL}	0.6
Number of fuel injections per engine crankshaft rotation		un./rot.	i	2
Fuel density	diesel	kg/m^3	ρ_F	840
	biofuel			870
Lower calorific value of fuel	diesel	J/kg	Q_F	34734000
	biofuel			32085000
Coefficient of reduction of diesel biofuel use efficiency when compared to diesel fuel *(Golub G. A., Chuba V. V., 2014)*	diesel	rel. un.	k_{CREB}	1
	biofuel			0.89
The angular velocity of the engine crankshaft		rad/sec	ω	207.5
Dependency ratios to determine the effective efficiency of the engine D-245		rel. un.	α	0.000006177
		rel. un.	β	0.001780996
		rel. un.	γ	0.271481621
Torque on the PTO shaft		N m^2	M_{PTO}	0
The translation ratio of the drive transmission		un.	i_{TR}	58.7
The efficiency of the drive transmission		un.	η_{TR}	0.88
The area of drag		m^2	S_{FAD}	4.5
The parameters for the operating unit				
The mass of the working unit (PRO-3)		kg	m_{WM}	820
Width of the tilled layer of soil		m	a	1.05
Depth of the tilled layer of soil		m	b	0.21
Parameters of the agro-technological environment				
The coefficient of slipping of the driving wheels at the width of the working unit	1.05 m	rel. un.	δ_S	0.178
	0.7 m			0.1554
	0.35 m			0.1483
The coefficient of rolling friction of the tractor wheels		rel. un.	f	0.09
The coefficient of air resistance		N sec^2/m^4	k_{AR}	0.75
The total coefficient of friction of the tool on the ground and the rolling friction of the support wheel		rel. un.	$f^{/}$	0.4
Soil deformation resistance	initial	N/m^2	k	29000
	final			36000
The ratio of the rate of the soil layer throwing away and the speed of the plough	initial	N sec^2/m^4	θ	1500
	final			2000

The parameters of MTU uniform motion on different types of fuel is characterized by the graphical dependencies (Fig. 3 and Fig. 4), which correspond to the time interval from 0 to 5 seconds (at the initial values of the parameters according to table 1).

At the 5th second at point "A" (Fig. 3 and Fig. 4) it is simulated one-time increase in soil resistance by changing the values of the soil deformation resistance and the ratio of the drop rate from the initial values to the final ones (according to table 1).

As a result of the increase in soil resistance, the load on the engine increases, leading to a decrease in the engine speed and slowing the MTU movement down (Fig. 3).

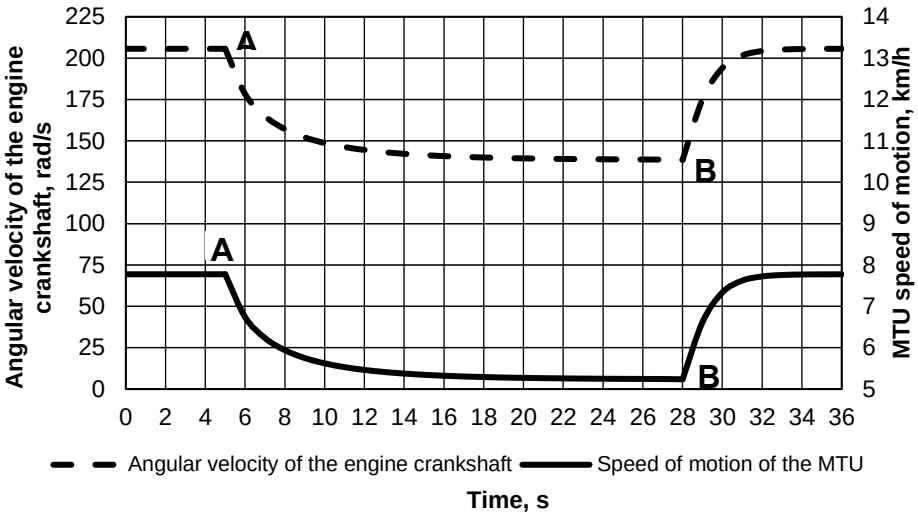

Fig. 3 - Dynamics of high-speed characteristics of the engine and MTU after changing the load and the subsequent change in fuel supply

If the fuel cycle is constant, reducing the engine speed will reduce the total fuel consumption (Fig. 4). As a result, such a system will try to find its new state of equilibrium. If this condition occurs with the parameters that are in the operating range of the internal combustion engine, the MTU stabilizes its movement at a low speed and engine speed and lower hourly fuel consumption. The course of this process is observed in the graphs (Fig. 3) and (Fig. 4) from the 5th to the 28th seconds. In the future, the MTU will come to a new mode of fuel supply, engine power and resistance of the unit, at which it will be possible to stable movement(Fig. 3 and Fig. 4).

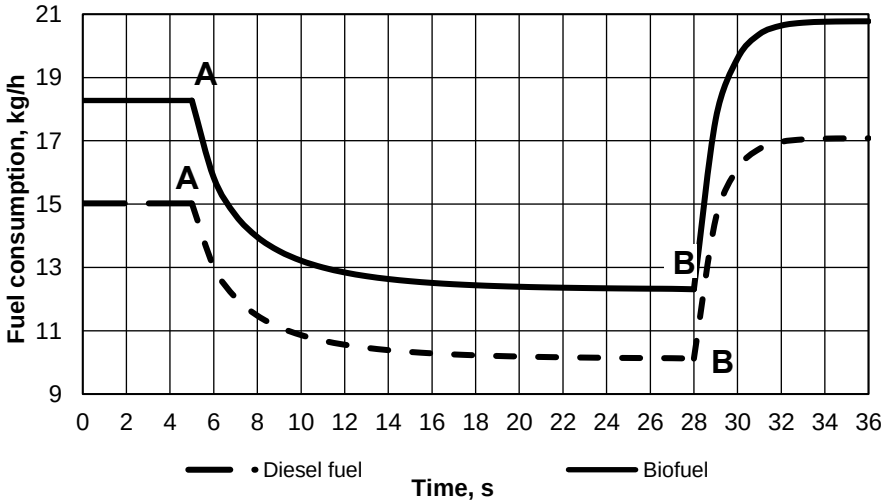

Fig. 4 - Dynamics of fuel consumption with increasing load and fuel supply

Section "A-B"(Fig. 3) characterizes the duration of the transition process to reduce the angular velocity of rotation of the engine crankshaft due to increased load at a constant cyclic fuel supply. The graphs of Fig. 3 and Fig. 4 from the 28th to 36th seconds simulate the process of the MTU speeding with an instant increase in fuel supply, providing the MTU output at the initial speed mode. The increase in the cyclic fuel supply at point "B" is simulated by changing the initial values of the active stroke of the plunger pair of the high-pressure fuel pump from the initial values to the final ones (according to table 1). Due to the increase in fuel flow, it is observed transient speeding of the MTU, ongoing for 6 seconds. During this time, the MTU is gaining initial speed and gains the equilibrium mode of the engine power and the resistance of the unit.

The analysis of the obtained dependences showed that at the same load and its change, for different types of fuel, the changes in the speed characteristics of the engine and the MTU (Fig. 3) occur under the same laws; it should be noted the difference in fuel consumption (Fig. 4). The difference in fuel consumption when working on diesel fuel and diesel biofuel, is associated with differences in the lower calorific value, fuel density, as well as a decrease in fuel combustion efficiency when working on diesel biofuel.

Since the transient processes of work of the engine and the MTU have a short-term character, the dependences of the hourly and specific fuel consumption for the uniform motion of the MTU in the performance of technological operations are obtained from the mathematical model of the MTU motion dynamics. This allows further optimization of the operational performance of the MTU.

Based on the equation (14), at a constant MTU speed and, accordingly, a constant angular velocity of the crankshaft, the expression for the calculation of the hourly fuel consumption takes the form:

$$G_{HFC} = \frac{3600\omega\left(C\omega^2 + H + I\right)}{Q_F k_{CREB}\left(\alpha\omega^2 + \beta\omega + \gamma\right)\left(1 - \delta_Б\right)\eta_{TR} i_{TR}}; \quad (15)$$

where: G_{HFC} – fuel consumption per hour, kg/h.

Eq.15 describes the relationship between the properties of the agro-technological environment, the design parameters of the working unit, fuel characteristics, and performance indicators of the MTU.

To verify the adequacy of the obtained theoretical dependence (15), a comparison of theoretical and experimental data is performed (Fig. 5). Simulation of the hourly fuel consumption change is performed when the traction resistance changes during ploughing. The change in traction resistance was performed by changing the width of the working unit. The experimental values of fuel consumption when changing the width of the trapping of the working unit and with using each type of fuel are represented by dots. The theoretical dependence is calculated using the expression (15), based on the values of the corresponding parameters (table 1), which characterized the MTU, fuel and soil properties in the experimental studies. The lines represent the theoretical values of fuel consumption when changing the working unit width and with using each type of fuel.

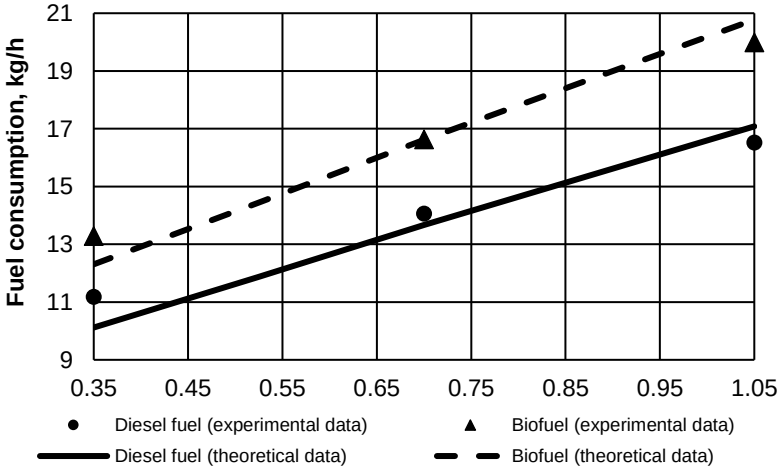

Fig. 5 - Dependence of the hourly fuel consumption on the variable traction resistance of the unit during the operation of the MTU

The index for determining the values of experimental and theoretical dependence of change in fuel consumption per hour on change in width of the unit capture calculated according to the methodology *(Dospehov B. A., 1985)*, for diesel fuel is η^2 = 0.933, and for diesel biofuel is η^2 = 0.968 (table 2).

The value of the determination index at the level of 0.933 and 0.968, for the corresponding type of fuel, allows asserting the adequacy of the obtained theoretical dependence (15) to experimental data, and also allows recommending the obtained model for modeling the parameters of the MTU.

As a result of the research, a mathematical model of MTU motion dynamics was developed. The resulting model establishes the relationship between the operational and structural parameters of the MTU, the parameters of the agro-technological environment and fuel characteristics. This takes into account the relationship between load, fuel type, fuel injection, the angular velocity of the engine crankshaft and the design parameters of the MTU.

A comparative study of the theoretical dependence of fuel and experimental data suggests the possibility of applying the obtained results to perform the simulation of driving dynamics and performance of the MTU on any tractor or power unit. The resulting model of the motion dynamics fits to perform the simulation of the MTU performance depending on the properties of agro-technological environment, fuel characteristics, modes of operation of the internal combustion engine, and any working bodies of agricultural machinery.

Table 2

Calculation of the index for determining the experimental and theoretical values of the influence of the MTU working unit width on the fuel consumption per hour

Width of capture of the working unit, m	Fuel consumption per hour, kg/h		Squared deviation of experimental values		Determination index
	calculated	experimental	from the general arithmetic value	from theoretical	
Diesel fuel					
0.35	10.118	11.18	12.2698	1.1277	0.933
0.7	13.662	14.06	0.0017	0.1584	
1.05	17.082	16.51	11.9795	0.3226	
The sum of the values	40.863	40.75	24.251	1.6088	
Biofuel					
0.35	12.307	13.27	1.726	0.945	0.968
0.7	16.619	16.63	8.987	0.000	
1.05	20.778	19.98	51.224	0.631	
The sum of the values	49.704	49.88	61.937	1.576	

The obtained results allow checking design solutions in the development of new working bodies, as well as optimizing the parameters and modes of the MTU operation. In addition, it allows determining the impact of the agro-technological environment characteristics and fuel characteristics on the performance of the MTU.

The further research will improve the resulting mathematical model of the MTU dynamics by clarifying the causes and nature of the formation of slipping, rutting, parameters of the interaction of the wheel with the fertile soil layer. This will make it possible to more fully characterize the processes of interaction between MTU and agro-technological environment. Clarification of the essence of the emergence of the driving force and the forces of resistance to movement will expand the number of parameters and relationships characterizing the MTU work.

This will provide dependencies that will more fully characterize the work of the MTU and increase the accuracy of mathematical modeling.

CONCLUSION

The conducted studies have established the relationship between the operational and structural parameters of the power unit, the working unit and the properties of the agro-technological environment. The mathematical model of the transition process of moving the MTU, which determines the change in angular velocity of the power unit engine crankshaft depending on the resistance of agricultural technology, environment, width, and depth of working unit capture, gear ratios and power unit drivetrain efficiency, as well as the type and characteristics of the used fuel. The simulation of transient processes of MTU motion during the technological operation of plowing is carried out. It is found that the transition process, caused by an increase in the resistance of the agro-technological environment by about 20%, causes the transition mode which lasts for 23 seconds and leads to an increase by 13.7% of the hourly fuel consumption of MTU. The resulting mathematical model can be used to simulate the work of MTU on the basis of other brands of tractors when aggregated with other working machines and on other types of soils using different fuels.

As a result of research, the analytical dependence of the hourly fuel consumption on the operational and design parameters of the power unit, the working unit and the properties of the agro-technological environment with uniform motion of the MTU is obtained. Studies of the effect of the working unit width on the hourly fuel consumption during the technological operation of plowing have shown that the deviation of the theoretical and experimental data is in the range of 2.8 to 9.5% depending on the width of the capture. The index for determining the obtained experimental and theoretical values for diesel fuel is $\eta^2 = 0.933$, and for diesel biofuel – $\eta^2 = 0.968$.

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