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Estimation of Operation Efficiency of Machine-Tractor Units Equipped with Constant Power Engines.

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ABSTRACT

Numerous published data evidence positive influence of the length of constant power range on power and technical-economical properties of internal combustion engine (ICE) and total operating unit, but the length of constant power range is determined by external regulatory characteristic of ICE which is plotted by consecutive load increase from zero to total load.The article attempts to estimate the deformation rate of constant power range at alternative pattern of external load. This is aided by probability coefficient p .

Keywords:mathematical model, constant power engine, constant power range length, probability factor p .

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INTRODUCTION

Nowadays there is a trend to increase adjustability factor of engines installed on up-to-date tractors. The most challenging solution in this field is development constant power engines (CPE) operating with constant power in wide range of rotation frequencies of engine shaft.

This facilitates continuous and automatic regulation of haulage and traveling speed of tractor at actually 100% use of CPEpower and high fuel efficiency.

The use of CPEoffers exciting possibilities to improve tractor motor-transmission units.

Analysis of tractor types delivered recently for testing at North Caucasian machine testing station revealed that all of them are equipped with engines, which according to Standard 20000 can be classified as constant power engines. They are John Deere, Massey Ferguson, Fendt, VERSATILE, VT-4S150DMand so on.

After bench testing (determinate load) it was established that the length of constant power range in terms of torque varies greatly on the range of 13-46%. However, under actual operation conditions, depending on the type of performed agricultural task, MTU traveling speed, soil properties of relief, upon motion of tillage combine statistical properties of hanger resistance $P_{\kappa p}$ vary, thus influencing on engine properties.

Unsteady haulage and its influence on diesel engine were studied by many researchers: Boltinskiy[1], Iofinov[2], Ageev[3] and others.

In particular, Prof. Ageevmentioned that low reserve of engine torque decreases tractor capacity. Capacity decrease depends on coefficient of variation of external load. It was established experimentally by Eminbeili[4] that at lower by 4-6 % reserve of torque the diesel engine properties decreases so that tractor cannot perform plowing tasks, it is required to provide at least 15-18 % torque reserve.

EXPERIMENTAL

In our studies in order to estimate the influence of external impacts on MTUoutput parameters we apply probability-statistic method developed elsewhere [5]. Its essence is that MTUis considered as an "input-output" model. Input X and output Y variables are interrelated, this interrelation is determined by means of determinate functional dependence $Y = f(X)$ at known distribution law [phi]. The function $Y = f(X)$ is determined at approximation of bench performance of engine or haulage property of MTU tractor. In order to visually present the values of effective power and corresponding values of rotation frequency of engine shaft 2D cross sections of response surface were provided (Fig. 1,a, b).

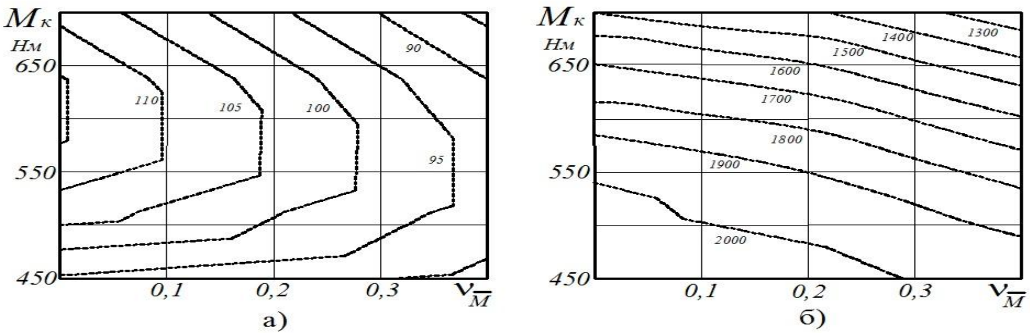

Fig.1. 2D cross section of response surface characterizing alteration of effective power (a) and engine shaft RPM (b) as a function of torque and coefficient of variation.

With increase in coefficient of variation of external load [nu] from 0 to 33.3% the bench characteristic is deformed and, respectively, the length of constant power range decreases (Fig. 2 a).

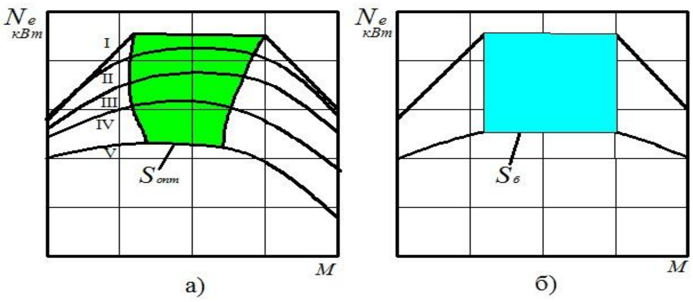

Fig.2. Diagram of validation of optimum and basic surface area.

In order to obtain quantitative estimation of deformation rate of constant power range at various values of load variations we introduce the coefficient p [6]:

$$p = S_{opt} / S_{б} , \qquad (1)$$

where S_{opt} is the surface area corresponding to optimum area (Fig.1 a); S_b is the basic surface area corresponding to such ideal case when at increase in load variation the constant power range is retained (Fig 1 b).

The coefficients p, calculated by our program for various tractors equipped with CPE, are listed in Table 1 [7].

Table 1:Coefficient p for various engines

Coefficient p	Engine specification			
	D-442-VSI-3 VT-4S150D	BF06M2012C ATM-3180	PE6068B695436 John Deere	Massey Ferguson
	0.69	0.80	0.25	0.44

Initial data for the program are the results of bench tests. After starting of calculations the program provides maximum power values and corresponding torques in the range of $0 \le \upsilon \le 0{,}333$ with increment of 0.01 and plots curve. Thus obtained area, highlighted in Fig. 3, corresponds to optimum operation range for this engine.

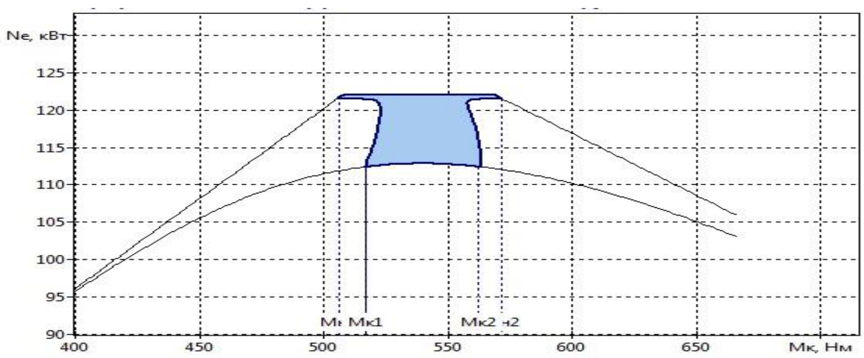

Fig.3. Optimum range for BF06M2012C engine.

In all points of the highlighted area (Fig. 2) the effective power N_e has its maximum not "in a point" but at the range of definite length. The range length will vary from maximum at coefficient of variation $\upsilon = 0$ иto minimum at $\upsilon = 0.333$.

There are numerous methods of optimization [8,9,10,11,12], but all they are valid when extreme value of target function is "in a point". In our case the question is to determine extreme value of function,

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which at significant variation of argument retains its own value at maximum. Therefore, conventional research methods in this case provide wrong results.

In order to determine probability coefficient p and maximum values of effective power we used the following algorithm in the program (Fig. 4).

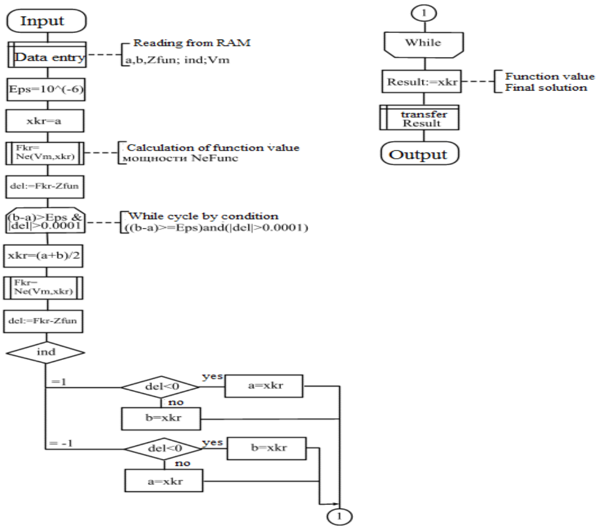

Fig.4. Developed algorithm.

RESULTS

Composition of MTU is determined by calculations or experimentally. In practice experimental approach is applied on the basis of recommendations of regular regional technological specifications. After selection of MTU its operation speed should be determined and corresponding gear.

Operation speed of all units is limited first of all by quality of task fulfillment. In addition, for hauling units it is limited by roadholdproperties, and for hauling-driving and self-propelling units it is limited by throughput capacity and engine power.

In practice MTU operation speed is selected on the basis of readings of RPM and speed meter installed on up-to-date tractors. With known range of allowable for agricultural tasks speeds of a given agricultural machine the tractor gear is determined by speedometer, the MTU should be in this range.

The engine load rate is determined by shaft RPM. Operation should be performed at shaft RPM slightly above than rated value (indicated in speed and RPM meter).

For CPEthe optimum loads in terms of effective power maximum forms surface area S_{opt}, which characterizes the region of MTU efficient operation. Constant engine power in wide ranges will provide the highest MTU productivity and efficiency.

That is, it is possible to arrange MTU from the point of view of rational composition and operation modes on the basis of known effective power in the optimum region. The optimum region is characterized by a set (M_k, v_M) of two random variables: engine torque M_k and coefficient of load variation v_M, that is, the two-dimensional random variable is meant.

Probability of controlled parameter (M_k, v_M) in the region S_{opt} can be determined by the equation:

$$P = ((M_k, v_M) \subset S_{opt}) = \iint f(M_k, v_M) dM_k dv_M \quad , (2)$$

where $f(M_k, v_M)$ is the density of combined distribution of two-dimensional continuous random variable (M_k, v_M).

The distribution density of two-dimensional random variables is expressed by the equation:

$$f(M_k, v_M) = \frac{1}{2 \cdot \pi \cdot \sigma_{M_k} \cdot \sigma_{v_M} \cdot \sqrt{1-r^2}} \cdot \varphi(M_k, v_M), \quad (3)$$

where r is the correlation coefficient of two random variables M_k and v_M .

On the basis of previous studies and experimental data, obtained upon testing of hauling MTU based on VT-4S150DM tractor, gradation of usage of major power performances in terms of major tasks was obtained (Table 2).

Table.2. Gradation of usage of tractor power parameters in terms of major tasks

Properties	Major tasks		
	Seeding	Secondary tillage	Primary cultivation
	$0 \le v_M \le 10$	$10 \le v_M \le 20$	$20 \le v_M \le 30$
$\lambda_{\overline{N}_{кр}}$	1.000 – 0.976	0.976 – 0.871	0.871 – 0.782
$\lambda_{\overline{N}_e}$	1.000 – 0.981	0.981 – 0.912	0.912 – 0.837
$\lambda_{\overline{G}_T}$	1.000 – 0.989	0.989 – 0.944	0.944 – 0.893
$\lambda_{\overline{g}_e}$	1.000 – 1.018	1.018 – 1.045	1.045 – 1.076
$\lambda_{\overline{M}_k}$	1.000 – 0.951	0.951 – 0.931	0.931 – 0.894
$\lambda_{\overline{n}_д}$	1.308 – 1.037	1.037 – 1.007	1.007 – 0.989

Taking into account the gradation of usage of tractor power parameters in terms of technological tasks and power consumption of the process, Fig. 5 illustrates the surface area corresponding to efficient use of CPEpower separated into corresponding areas. The points, applied to the diagram, visually illustrate the MTU set and selection of rational operating gear for this technological process.

Thus, the points *F,S,N*correspond to operation of sowing unit VT-4S150DM+SP-16+4SZP-3,6Bin second, third, and fourth gear, respectively, and the points *K*and *L*to operation of plowing unit VT-4S150DM+PLN-5-35 in second and third gears.

Optimum loads of CPEupon disk harrowing and cultivation correspond to the points *A,B,C*and *D,G,E* (units VT-4S150DM+BDM-3,6x4 and VT-4S150DM+SP-16+4KPS-4+16BZSS-1 in third, fourth and fifth gear, respectively). While analyzing Fig. 5 it is possible to conclude that for VT-4S150DMtractor the optimum points in terms of efficiency are second, third and fourth gears. Therefore, on the basis of known controllable parameter in optimum area it is possible to arrange correctly MTU and to select operation gear.

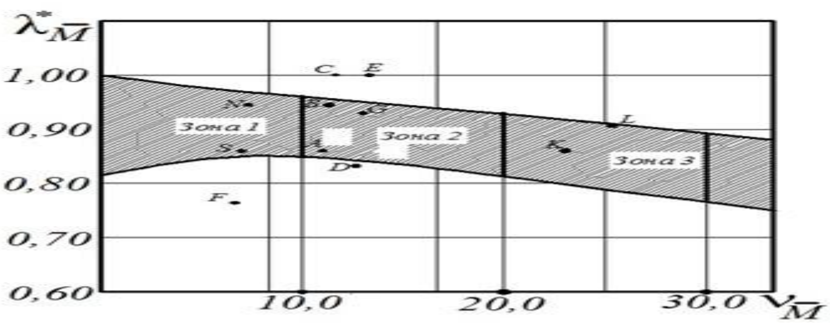

Fig.5. Gradation of optimum operation range of MTU based on VT-4S150DMtractor (in terms of CPE load) as a function of type of technological task (Area 1 – corresponds to the least power consuming tasks; Area 2 – corresponds to tasks of medium power consumption; Area 3 – corresponds to the most power consuming tasks).

DISCUSSION

With certain assumptions upon haulage testing of tractors: no slipping, determinate pattern of external load (such situation can be approximately simulated, for instance, during testing in concrete track), it is possible to assume that the progress of haulage capacity will be similar to behavior of effective power. That is, we can speak about the range of constant haulage capacity (Fig. 6).

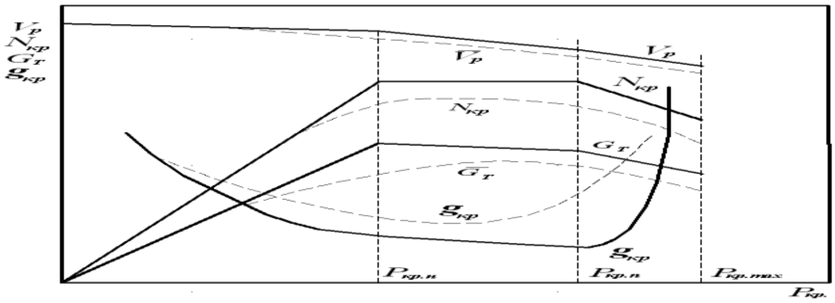

Fig.6. Flowchart of probability estimation of power properties of MTU.

On the basis of these considerations and knowing that the distribution density of haulage obeys the normal law, dependences for power and technical-economical performances based on tractor haulage characteristic were obtained for MTU equipped with constant power engines.

Expectation of MTU travelling speed (Fig. 6) is determined by the equation:

$$\bar{v}_p = \int_{-\infty}^{P_{кр.н}} f_1(P_{кр})\varphi(P_{кр})dP_{кр} + \int_{P_{кр.н}}^{P_{кр.п}} f_2(P_{кр})\varphi(P_{кр})dP_{кр} + \int_{P_{кр.п}}^{\infty} f_3(P_{кр})\varphi(P_{кр})dP_{кр} \qquad (4)$$

where

$$f(P_{кр}) = \begin{cases} f_1(P_{кр}) = A_1 + B_1 \cdot P_{кр} \quad при \;\; 0 \le P_{кр} \le P_{кр.н} \\ f_2(P_{кр}) = A_2 + B_2 \cdot P_{кр} \quad при \;\; P_{кр.н} \le P_{кр} \le P_{кр.п} \\ f_3(P_{кр}) = A_3 + B_3 \cdot P_{кр} \quad при \;\; P_{кр.п} \le P_{кр} \le P_{кр.\max} \end{cases} \qquad (5)$$

$A_1, A_2, A_3, B_1, B_2, B_3$ are the constants and slope coefficients determined by engine haulage characteristic ; $P_{кр.н}, P_{кр.п}, P_{кр.\max}$ are the rated, ultimate and maximum haulage of MTU, respectively, N.

After substitution of the variable $t = (P_{кр} - \overline{P}_{кр}) / \sigma_p$ into Eq. (4) and taking into account Eq. (5), we have:

$$\bar{v}_p = 0{,}5 \cdot (a + b \cdot \overline{P}_{кр}) + (a_1 + b_1 \cdot \overline{P}_{кр}) \cdot \Phi(t_н) + (a_2 + b_2 \cdot \overline{P}_{кр}) \cdot \Phi(t_п) - -\overline{P}_{кр} \cdot v_p \cdot [b_1 \cdot \varphi(t_н) + b_2 \cdot \varphi(t_п)] \qquad (6)$$

where $\Phi(t_н), \Phi(t_п), \varphi(t_н), \varphi(t_п)$ are the tabulated functions; $t_н = (P_{кр.н} - \overline{P}_{кр}) / \sigma_p$, $t_п = (P_{кр.п} - \overline{P}_{кр}) / \sigma_p$ are Laplace function arguments; a, a_1, a_2, b, b_1, b_2 are the constants; $\overline{P}_{кр}, v_p$ are the average values and coefficient of variation of MTU haulage.

Variation of MTU output parameters with probability pattern of external load is estimated by means of probability coefficient [5]:

$$\lambda_{\bar{v}_p} = \frac{\bar{v}_p}{v_б}, \qquad (7)$$

where $\bar{v}_p$ is the expectance of MTU travelling speed; $v_б$ is the basic value of MTU travelling speed determined by haulage characteristic.

The highest deviations of expectances of MTU travelling speed from the values determined by tractor regular specifications are observed at ultimate haulage for a given gear, that is, at $\lambda_{\bar{v}} = 1,0$ (Fig. 7).

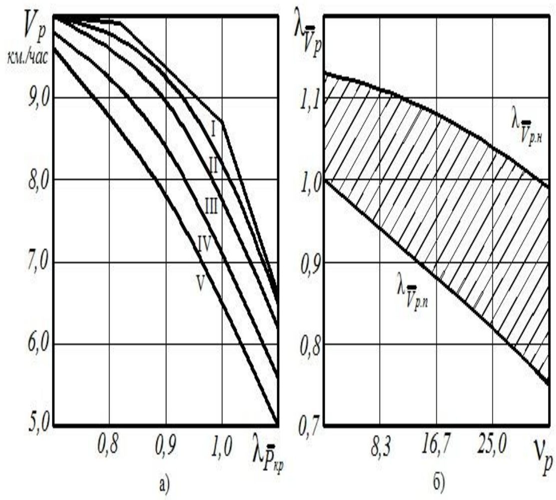

Fig.7. Variation of operation estimations of VT-4S150DMtractor as a function of load rate and coefficients of its variation v_p (I –0%; II – 8.3%; III – 16.7%; IV – 25.0%; V – 33.3%): a)- traveling speed v_p; b)- probability coefficient $\lambda_{\bar{v}_p}$

Expectance of tractor haulage capacity at probability pattern of external impacts and normal law of $P_{кр}$ argument distribution is determined by the equation:

$$\bar{N}_{кр} = \int_{-\infty}^{P_{кр.н}} f_1(P_{кр})\varphi(P_{кр})dP_{кр} + \int_{P_{кр.н}}^{P_{кр.п}} f_2(P_{кр})\varphi(P_{кр})dP_{кр}$$
$$+\int_{P_{кр.п}}^{\infty} f_3(P_{кр})\varphi(P_{кр})dP_{кр} \qquad (8)$$

The coupling function $N_{кр} = f(P_{кр})$ (Fig. 6) is established at approximation of haulage characteristic by three linear segments [2]:

$$f(P_{кр}) = \begin{cases} f_1(P_{кр}) = A_1^* + B_1^* \cdot P_{кр} \;\; при \;\; 0 \le P_{кр} \le P_{кр.н} \\ f_2(P_{кр}) = A_2^* + B_2^* \cdot P_{кр} \;\; при \;\; P_{кр.н} \le P_{кр} \le P_{кр.п} \\ f_3(P_{кр}) = A_3^* + B_3^* \cdot P_{кр} \;\; при \;\; P_{кр.п} \le P_{кр} \le P_{кр.\max} \end{cases} \qquad (9)$$

where $P_{кр.н}, P_{кр.п}$ are the rated and ultimate MTU haulage, kN; $A_1^*, A_2^*, A_3^* \; и \; B_1^*, B_2^*, B_3^*$ are the slope coefficients determined by tractor haulage characteristic (Table 1).

Taking into account the definite integrals:

$$\overline{N}_{кр}=0{,}5\cdot(a^{*}+b^{*}\cdot\overline{P}_{кр})+(a_1^{*}+b_1^{*}\cdot\overline{P}_{кр})\cdot\Phi(t_н)+(a_2^{*}+b_2^{*}\cdot\overline{P}_{кр})\cdot\Phi(t_п)-$$
$$-\overline{P}_{кр}\cdot v_p\cdot[b_1^{*}\cdot\varphi(t_н)+b_2^{*}\cdot\varphi(t_п)] \qquad (10)$$

where $a_1^*, a_2^*, a_3^*, b_1^*, b_2^*, b_3^*$ are the constants (Table 3).

Table.3. Slope coefficients and constants determined by haulage capacity of VT-4S150DM tractor

Coefficient	Equation формула	Numerical values	
		III gear	IV gear
A_1^*	-	0	0
A_2^*	$N_{кр}+(N_{кр.н}-N_{кр.п})/(k_2-1)$	80.200	77.500
A_3^*	$N_{кр.п}+(N_{кр.п}-N_{\max})/(k_1-1)$	183.600	203.676
B_1^*	$N_{кр.н}\ /\ P_{кр.н}$	2.819	3.295
B_2^*	$(N_{кр.п}-N_{кр.н})/(P_{кр.п}-P_{кр.н})$	0	0
B_3^*	$(N_{кр.п}-N_{\max})/(P_{кр.\max}-P_{кр.п})$	-3.007	-4.476
a^*	$A_1^*+A_3^*$	183.600	203.676
a_1^*	$A_1^*-A_2^*$	-80.200	-77.500
a_2^*	$A_2^*-A_3^*$	-103.400	-126.176
b^*	$B_1^*+B_3^*$	-0.188	-1.181
b_1^*	$B_1^*-B_2^*$	2.819	3.295
b_2^*	$B_2^*-B_3^*$	3.007	4.476
$N_{кр.н}, N_{кр.п}, N_{\max}$ – haulage capacity corresponding to rated, ultimate and maximum haulage loads of the unit, kN; $k_1=P_{кр.\max}\ /\ P_{кр.п}\ и\ k_2=P_{кр.п}\ /\ P_{кр.н}$ – coefficients.			

The coefficient $\lambda_{\overline{N}_{кр}}$ accounting for variation of average values (expectances) of tractor haulage capacity at unsteady load is determined by the equation:

$$\lambda_{\overline{N}_{кр}}=\frac{\overline{N}_{кр}}{N_б}, \qquad (11)$$

where $\overline{N}_{кр}$ is the average haulage capacity, kW; $N_б$ is the basic power at determinate function $N_{кр}=f(P_{кр})$ determined by haulage capacity (at $v_p=0$), kW.

The highest power values $N_{кр}$ are observed in the load range of $\lambda_{\overline{P}_{кр}}=0{,}8...1{,}0$, that is, in the range of constant haulage capacity (Fig. 8 a).

Variation of coefficient $\lambda_{\overline{N}_{кр}}$ for third and fourth gear as a function of coefficient of variation v_p is illustrated in Fig. 8, b; the maximum deviation of the coefficient $\lambda_{\overline{N}_{кр}}$ is 24.9% and 29.6% at the coefficient of variation $v_p = 33,3\%,$ for third and fourth gear, respectively.

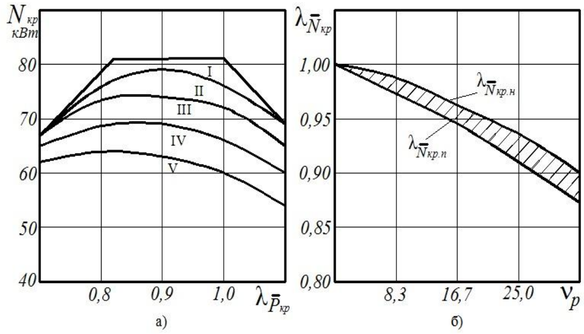

Fig.8. Variation of operation estimations of VT-4S150DMtractor as a function of load rate $\lambda_{\overline{P}_{кр}}$ and coefficient of its variation v_p (I –0%; II – 8,3%; III – 16,7%; IV – 25,0%; V – 33,3%): a)- haulage capacity $\overline{N}_{кр}$; b)- probability coefficient $\lambda_{\overline{N}_{кр}}$.

Expectance of MTU hourly output as a function of engine haulage capacity is calculated by the equation:

$$\overline{W}_{ч} = c_w \cdot \overline{N}_{кр} \qquad (12)$$

where $c_w = 0,36 \cdot \tau \cdot k_a^{-1}$; $\overline{N}_{кр}$ is the expectance of tractor haulage capacity, kW; τ – is the operation factor of shift time; k_a is the specific resistance of MTU, kN/m.

Coefficient accounting for variation of MTU output upon oscillations of external load $\lambda_{\overline{W}_{ч}}$ is determined by the equation:

$$\lambda_{\overline{W}_{ч}} = \frac{\overline{W}_{ч}}{W_{ч.б}}, \qquad (13)$$

where $\overline{W}_{ч}$ is the current hourly MTU output, determined by Eq. (10), ha/h; $W_{ч.б}$ is the basic (ultimate) hourly MTU output, ha/h.

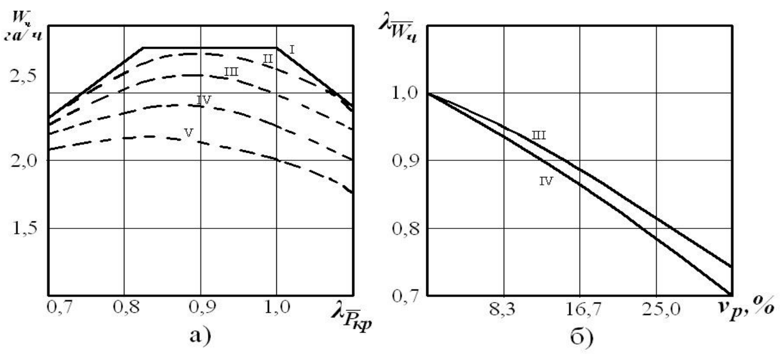

Fig.9. Variation of operation estimations of VT-4S150DM tractor as a function of load rate $\lambda_{\overline{P}_{кр}}$ and coefficient of its variation v_p (I – 0%; II – 8.3%; III – 16.7%; IV – 25.0%; V – 33.3%): a)- hourly output $\overline{W}_ч$; b)-probability coefficient $\lambda_{\overline{W}_ч}$.

MTU output at probability load stipulated by random pattern of external factors is not a constant value. Numerical characteristics of MTU output depend on average value and measure of load dispersion. Regularities of expectance variation of MTU output at various load modes and fixed measure of dispersion of the variable $P_{кр}$ do not differ from regularities of variation of haulage capacity.

MTU should operate in the load range of $\lambda_{\overline{P}_{кр}} = 0,8...1,0$ (Fig. 9).

CONCLUSIONS

Using the improved algorithm and developed program it is possible to establish maximum values of effective power and corresponding values of torque.

The coefficient p has probability meaning and characterizes probability of optimum load values in basic area. That is, the higher is the coefficient p, the higher is the probability of controllable parameters in optimum area.

Therefore, we introduce universal estimating index which enables comparison of MTU based on tractors with constant power engine.

The proposed mathematical models obtained by approximation of tractor haulage characteristic make it possible to estimate the influence of varying external factors on MTUoperation and to establish rational operational modes and parameters for MTUequipped with constant power engines. In order to verify the adequacy of these models it will be required to perform testing of tractors on various agricultural backgrounds (in order to confirm the made assumptions).

Taking into account the existence of constant power range in tractor haulage characteristic in actual operation conditions with various agricultural machines, its mathematical description is interesting from scientific and practical points of view.

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