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Designing Mathematical Models of Geometric and Technical Parameters for Modern Road-Building Machines Versus the Main Parameter of the System

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***Abstract* – Fleet equipping for toting auto road construction should be planned with the account of projected road schemes, regional peculiarities and target growth of labour capacity. The state-of-the-art IT solutions should be found for programming methods. It has been determined that application of the developed methodology for determining technical and geometrical parameters of the machines as function of operational conditions in collaborative work in the complex, connected with the chief parameter of the machine allows determining at the stage of specifying technical requirements the scheme of the designed equipment with CAD systems. This methodology of formation the set of parameters for designing machine scheme by determining similarity coefficient values on the analysis of sample-machine parameters of the same dimension range with the account of certain operational conditions can be used for receiving the initial approximation image of other types of earth-moving machinery.**

Keywords* – designing, mathematical model, equation, methodology, algorithm.

I. Introduction

Optimal relationship between basic parameters of the modern road-building machines can be determined by similarity theory. It allows conducting the search basing on the interrelation mechanism between separate elements of the system applying methods of statistic analysis on corresponding stages. It should be noted that, the problem to determine optimal interrelations of parameters and geometrical elements of road-building machines should be considered as a part of the technical machine design assignment with CAD method.

There are works where similarity methods were used to determine relations between basic parameters of road-building machines without estimating their optimality [1-21]. These works have allowed establishing that main parameters of some machines by power, weigh and geometric parameters comply with general laws of similarity. It should be noted that similarity theory as a method of studying systems covers only quantitative characteristics of the process and for quality characteristics of the process development additional methods should be applied.

II. Materials and methods

Values of the main technological and geometrical parameters of road-building machines as some mechanical systems in design conditions are determined by classical mechanics regularities. The system of equations describing the operational process of the machine in determining similarity conditions of earth-moving machinery by basic technical and geometrical parameters has been considered in the simplified form. To yield the formulas of similarity by main geometric parameters it is necessary to derive an equation of movement of the studied machine in the operating and transport mode, considering an earth-moving machine as a mechanical system having seven masses and one degree of freedom (figure 1). Similarity relations between basic technical parameters of earth-moving machines are determined by physics of the operational process of the considered group of machines.

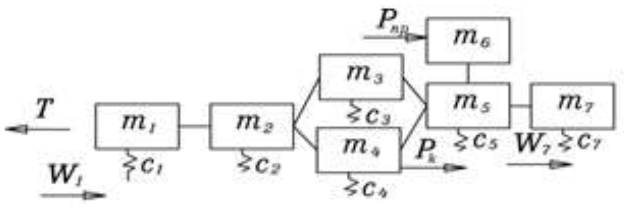

Fig. 1. Mechanical equivalent of the scraper aggregate as a system with seven masses

Figure 1 has the following symbols:

m_1 is the mover reduced mass; m_2 is the reduced mass of the scraper arm arc; $m_3 m_4$ −are reduced masses of the left and right draft frames correspondingly; m_5 −is the reduced mass of the scraper bowl without the front shutter; m_6 −is the reduced mass of the shutter; m_7 is a reduced mass of the rear axle; T is a pulling force; W1 reaction to the front wheel group movement; Re is extraction resistance; Rss is the soil slide force acting onto the front shutter in the scraper bowl; W7 is reaction to the front wheels movement; C1…C7 is unit stiffness of the nodes mentioned above.

This case is described by the following system of equations:

a) transport movement mode

$$\mathrm{m1}\frac{d^2x_1}{dt^2} + c_1x_1 = T - G_1 f \qquad (1)$$

$$\mathrm{m1}\frac{d^2x_1}{dt^2} + m_2\frac{d^2x_2}{dt^2} + c_1x_1 + c_2x_2 = T - (G_1 + G_2)f \qquad (2)$$

$$\mathrm{m1}\frac{d^2x_1}{dt^2} + m_2\frac{d^2x_2}{dt^2} + (m_3+m_4)\frac{d^2(x_3+x_4)}{dt^2} + c_1x_1 + c_2x_2 + \frac{1}{\frac{1}{c_3}+\frac{1}{c_4}}(x_3+x_4) = T - (G_1+G_2+G_3+G_4)f$$

$$\mathrm{m1}\frac{d^2x_1}{dt^2} + m_2\frac{d^2x_2}{dt^2} + (m_3+m_4)\frac{d^2(x_3+x_4)}{dt^2} + (m_5+m_6)\frac{d^2x_5}{dt^2} + c_1x_1 + c_2x_2 + \frac{x_3+x_4}{\frac{1}{c_3}+\frac{1}{c_4}} + (c_5+c_6)x_5 = T - (G_1+G_2+G_3+G_4+G_5+G_6)f - P_{пр}$$

$$\mathrm{m1}\frac{d^2x_1}{dt^2} + m_2\frac{d^2x_2}{dt^2} + (m_3+m_4)\frac{d^2(x_3+x_4)}{dt^2} + (m_5+m_6)\frac{d^2x_5}{dt^2} + m_7\frac{d^2x_7}{dt^2} + c_1x_1 + c_2x_2 + \frac{x_3+x_4}{\frac{1}{c_3}+\frac{1}{c_4}} + (c_5+c_6)x_5 + c_7x_7 = \mathrm{T} - Gf - P_{пр}$$

b) operational movement mode

$$\mathrm{m1}\frac{d^2x_1}{dt^2} + c_1x_1 = \mathrm{T} - G_1 f$$

$$\mathrm{m1}\frac{d^2x_1}{dt^2} + m_2\frac{d^2x_2}{dt^2} + c_1x_1 + c_2x_2 = T - (G_1+G_2)f \qquad (3)$$

$$\mathrm{m1}\frac{d^2x_1}{dt^2} + m_2\frac{d^2x_2}{dt^2} + (m_3+m_4)\frac{d^2(x_3+x_4)}{dt^2} + (m_5+m_6)\frac{d^2x_5}{dt^2} + c_1x_1 + c_2x_2 + \frac{x_3+x_4}{\frac{1}{c_3}+\frac{1}{c_4}} + (c_5+c_6)x_5 = T - (G - G_7)f - \mathrm{Pto}$$

$$\mathrm{m1}\frac{d^2x_1}{dt^2} + m_2\frac{d^2x_2}{dt^2} + (m_3+m_4)\frac{d^2(x_3+x_4)}{dt^2} + (m_5+m_6)\frac{d^2x_5}{dt^2} + m_7\frac{d^2x_7}{dt^2} + c_1x_1 + c_2x_2 + \frac{x_3+x_4}{\frac{1}{c_3}+\frac{1}{c_4}} + (c_5+c_6)x_5 + c_7x_7 = \mathrm{T} - Gf - P_k$$

There are assumptions and limitations in the system:

a) by coupling

$$m_5 = \frac{G_k}{g} + \frac{G_r}{g} \qquad (4)$$

б) by capacity

$$\mathrm{q} = \frac{G_r}{\gamma_r} \qquad (5)$$

в) let's assume that there are only elastic coupling in the system.

Criteria of similarity of the scraper-aggregate operation process shown as a seven masses dynamic system are determined by the analysis of the movement equations in the operating and transport mode.

For the accepted scheme a corresponding system of equations 2 and 3 leads to the following system of integral analogues:

a) transport mode

$$\frac{m_1l_1}{t^2} \sim c_1l_1 \sim T \sim G_1 f \qquad (6)$$

$$\frac{m_1l_1}{t^2} \sim \frac{m_2l_2}{t^2} \sim c_1l_1 \sim c_2l_2 \sim T \sim G_1 f \sim G_2 f$$

$$\frac{m_1l_1}{t^2} \sim \frac{m_2l_2}{t^2} \sim \frac{(m_3+m_4)(l_3+l_4)}{t^2} \sim c_1l_1 \sim c_2l_2 \sim \frac{l_3+l_4}{\frac{1}{c_3}+\frac{1}{c_4}} \sim T \sim G_1 f \sim G_2 f \sim G_3 f \sim G_4 f$$

$$\frac{m_1l_1}{t^2} \sim \frac{m_2l_2}{t^2} \sim \frac{(m_3+m_4)(l_3+l_4)}{t^2} \sim \frac{(m_5+m_6)l_5}{t^2} \sim c_1l_1 \sim c_2l_2 \sim \frac{l_3+l_4}{\frac{1}{c_3}+\frac{1}{c_4}} \sim (c_5+c_6)l_5 \sim T \sim G_1 f \sim G_2 f \sim G_3 f \sim G_4 f \sim G_5 f \sim G_6 f \sim P_{пр}$$

$$\frac{m_1l_1}{t^2} \sim \frac{m_2l_2}{t^2} \sim \frac{(m_3+m_4)(l_3+l_4)}{t^2} \sim \frac{(m_5+m_6)l_5}{t^2} \sim \frac{m_7l_7}{t^2} \sim c_1l_1 \sim c_2l_2 \sim \frac{l_3+l_4}{\frac{1}{c_3}+\frac{1}{c_4}} \sim (c_5+c_6)l_5 \sim c_7l_7 \sim T \sim Gf \sim P_{пр}$$

б) operational mode

$$\frac{m_1 l_1}{t^2} \sim c_1 l_1 \sim T \sim G_1 f \quad (7)$$

$$\frac{m_1 l_1}{t^2} \sim \frac{m_2 l_2}{t^2} \sim c_1 l_1 \sim c_2 l_2 \sim T \sim G_1 f \sim G_2 f$$

$$\frac{m_1 l_1}{t^2} \sim \frac{m_2 l_2}{t^2} \sim \frac{(m_3+m_4)(l_3+l_4)}{t^2} \sim c_1 l_1 \sim c_2 l_2 \sim \frac{l_3+l_4}{\frac{1}{c_3}+\frac{1}{c_4}} \sim T \sim G_1 f \sim G_2 f \sim G_3 f \sim G_4 f$$

$$\frac{m_1 l_1}{t^2} \sim \frac{m_2 l_2}{t^2} \sim \frac{(m_3+m_4)(l_3+l_4)}{t^2} \sim \frac{(m_5+m_6)l_5}{t^2} \sim c_1 l_1 \sim c_2 l_2 \sim \frac{l_3+l_4}{\frac{1}{c_3}+\frac{1}{c_4}} \sim (c_5+c_6)l_5 \sim T \sim G_1 f \sim G_2 f \sim G_3 f \sim G_4 f \sim G_5 f \sim G_6 f \sim P_к$$

$$\frac{m_1 l_1}{t^2} \sim \frac{m_2 l_2}{t^2} \sim \frac{(m_3+m_4)(l_3+l_4)}{t^2} \sim \frac{(m_5+m_6)l_5}{t^2} \sim \frac{m_7 l_7}{t^2} \sim c_1 l_1 \sim c_2 l_2 \sim \frac{l_3+l_4}{\frac{1}{c_3}+\frac{1}{c_4}} \sim (c_5+c_6)l_5 \sim c_7 l_7 \sim T \sim Gf \sim P_к$$

Corresponding invariable values are received from the system of integral analogues. As a result we receive the following similarity criteria:

$$\frac{ml}{t^2};\ \frac{cl}{T};\ \frac{l}{(\frac{1}{\frac{1}{c_л}+\frac{1}{c_к}})T};\ \frac{Gf}{T};\ \frac{P_к}{T};\ \frac{P_{пр}}{T}; \quad (8)$$

The received system of similarity criteria can be reduced. For this, some parameters in invariable dependencies are written in the form of known equations:

$$m=\frac{G}{g};\ T=G*\varphi_{сц} \quad (9)$$

Accepting that $G=\gamma l^3$ $l_j \sim l$ we receive

$$m\sim\frac{\gamma l^3}{g} \quad T\sim\gamma l^3\varphi_{сц} \quad W\sim\gamma l^3 f \quad (10)$$

After that similarity criteria can be written as:

$$\frac{V^2}{gl\varphi_{сц}};\frac{C}{\gamma l^2\varphi_{сц}};\frac{C\gamma l^3\varphi_{сц}}{2};\frac{P_к}{\gamma l^3\varphi_{сц}};\frac{f}{\varphi_{сц}};\frac{P_{пр}}{\gamma l^3\varphi_{сц}} \quad (11)$$

Excluding the same similarity criteria and accepting dimensionless criteria $\varphi_{сц}$ and f as separate invariants we can write:

$$\frac{V^2}{gl};\ \frac{C}{\gamma l^2};\ \frac{C\gamma l^3}{2};\ \frac{P_к}{\gamma l^3};\ \frac{P_{пр}}{\gamma l^3};\ \rho; f;\ \varphi_{сц};\ \alpha; \quad (12)$$

Criteria $\frac{P_к}{\gamma l^3}$ и $\frac{P_{пр}}{\gamma l^3}$ are the evolution of criteria determining interaction of the operating equipment with the soil and connecting the parameters of the soil cutting process with the machine weight. This condition can be determined so. These criteria $\frac{P_к}{\gamma l^3}$ and $\frac{P_{пр}}{\gamma l^3}$ can be substituted by the equivalent criteria. Value $P_к$ can be considered proportional to the sum of surface and mass resistant force.

$$P_к \sim P_1 + P_2, \quad (13)$$

where P_1 are resistance to excavation having the nature of mass forces, for example, resistance forces of the soil weight in the soil slide; P_2 resistant forces to excavation which are surface by nature, for example, soil resistance to shear and separation and so on.

$$P_к \sim \gamma_г l^3 t_{g\rho} + K_p l^2 \quad (14)$$

or

$$P_к \sim \gamma_г l^3 t_{g\rho} + \tau l^2 \quad (15)$$

K_p is resistivity constant to cut.

It follows that criterion $\frac{P_к}{T}$ or $\frac{P_к}{\gamma l^3}$ is equivalent to the following criteria:

$$\frac{\gamma_г l^3}{T};\ \frac{\tau l^2}{T};\ \rho;\ \frac{\gamma_г}{\gamma};\ \frac{\tau}{\gamma l};\ \frac{K_p}{\gamma l} \quad (16)$$

As $P_{пр} = K_{12}P_к$ then criterion $\frac{P_{пр}}{\gamma l^3}$ also can be substituted by similarity criterion, the analogue criterion

$$K_{12} = \frac{P_{пр}}{P_к} \quad (17)$$

Dividing criteria $\frac{K_p}{\gamma l}$ by criteria $\frac{\gamma_г}{\gamma}$ or criteria $\frac{K_p l^2}{T}$ by invariable $\frac{\gamma_г l^3}{T}$ results in a new criteria $\frac{K_p}{\gamma_г l}$

As $K_p=К_\tau * \tau$; $K_p = К_\sigma * \sigma$, where $К_\tau$ $К_\sigma$ are empirical coefficients we can write that

$$\frac{K_p}{\gamma_г l} \sim \frac{\tau}{\gamma_г l} \sim \frac{\sigma}{\gamma_г l} \quad (18)$$

With the account of these positions, the system of equations for the scraper aggregate equilibrium as a dynamic system allows receiving the following similarity criteria:

$$\frac{V^2}{gl};\frac{\gamma_г l^3}{T};\frac{\tau l^2}{T};\frac{l^3}{G.K_p};\frac{K_p}{\gamma_г l^3};\frac{cl}{G};\frac{cl^2\gamma_г}{2};\frac{q\gamma_г}{G};\frac{l^3}{q};\rho; f;\ \varphi_{сц};\ \alpha; \quad (19)$$

Criteria $\rho; f;\ \varphi_{сц};\ \alpha;$ determine similar conditions of studying the system.

The parameter scales of such machines are related by the equations:

$$К_к = К_\gamma * К_l \quad К_T = К_\gamma * К_q \quad К_G = К_q * K_l^3 \quad K_V = K_g K_l^{1/2}$$
$$К_q = K_l^3 \quad К_T = К_G \quad K_\varphi = 1 \quad K_f = 1 \quad K_{\varphi_{сц}} = 1 \quad К_\alpha = 1 \quad (20)$$

In natural conditions for machines of different nominal size when linear dimensions change in some of the basic similarity criteria there are other changes, some criteria do not change, or change insignificantly. To provide approximate similarity of scraper aggregates of different nominal sizes the following equation should be observed:

$$К_р = К_\gamma * K_l^3 \quad К_р = К_к * K_l^3 \quad (21)$$

For the most likely operational case when the model and the prototype operate in similar soils $К_\gamma = I, К_к = I$ approximation method is implemented by observing conditions of different dimensions of linear scales for the cutting depth $К_h$ and cutting width $К_в$. When $K_l^3 = К_q$ accepting that the linear dimensions scale of the scraper bowl and dragging slide do not depend on the scale of the cut depth, we receive from the equation:

$$К_h = \frac{К_q}{К_в} \quad (22)$$

Machines in real conditions can change the cut depth in wide scales irrespective of other linear dimensions of the system. It ensures similarity conditions following from the criterion $\frac{К_р}{\gamma_г l}$. Besides the transport mode of the machine which takes the main part of the operation cycle has no restriction in these criteria.

Basing on the central tenet of the similarity and modeling theory, static analysis of the technical and geometrical parameters values of the existing machines, functional dependencies of geometric and technical parameters have been received, versus the main scraper parameter, which have been determined by physics analysis of the operation process of the studied machine.

Mathematical dependencies of the basic elements for the scraper aggregate versus the main parameter and can be shown as:

length

$$L=K_L q^{1/3} \quad (23)$$

width

$$W=K_в q^{1/3} \quad (24)$$

height

$$H=K_н q^{1/3} \quad (25)$$

Longitudal wheel-base

$$l=K_l q^{1/3} \quad (26)$$

Cross wheel - base

$$w=K_в q^{0,39} \quad (27)$$

The scraper bowl dimensions and form influence filling resistance and unloading speed which influences the efficiency of the machine. But for the scrapers of the greater capacity, the bowl width determined by the similarity formulas exceeds the railway equipment that complicates transportation by the railways. That is why; analytical dependencies expressing the scraper bowl geometry are divided into two subgroups – for the scraper less than 26 m3 and greater than 26 m3. The boundary between these subgroups is determined from the conditions of maximum-permissible width of the railway equipment.

For scrapers less than 26 m3

$$h=K_h * q^{\frac{1}{3}} \quad (28)$$

$$l_1 = K_{l_1} q^{1/3} \quad (29)$$

$$l_2 = K_{l_2} q^{1/3} \quad (30)$$

$$B_1 = K_{B_1} q^{1/3} \quad (31)$$

$$B_2 = K_{B_2} q^{1/3} \quad (32)$$

For scrapers greater than 26 m3

$$h=k_{h^1} * q^{1/3} \quad (33)$$

$$l_1 = K_{l_1^1} q^{1/3} \quad (34)$$

$$l_2 = K_{l_2^1} q^{1/3} \quad (35)$$

$$B_1 = K_{B_1^1} q^{1/3} \quad (36)$$

$$B_2 = K_{B_2^1} q^{1/3} \quad (37)$$

For front wheels

$$D_n = K_D q^{0.37} \quad (38)$$

$$A_n = K_A q^{1/2} \quad (39)$$

$$D_3 = K_3 * q^{0.37} \quad (40)$$

$$A_3 = K_3 * q^{1/2} \quad (41)$$

where h is a bowl height in m, l_1 is a bowl length in m; l_2 is a bowl length in m; B_1 is a bowl width in m; B_2 is a cut width in m; D_n D_3 are the diameters of the front and rare wheels correspondingly; $A_n A_3$ is a width of the front and rare wheels.

In formulas (38, 39, 40, 41) the similarity coefficient values are determined by statistics analysis of separate parameters of the existing machines. But for the iteration model of machine model formation with CAD system this method is not correct enough as qualitative and quantitative weight of a separate point in a static model and the probable result do not reflect main tendencies in changes of the studied parameter which is proved by the central tenet of the theory of probability - mathematical expectation of the argument and not a mathematic expectation of the function under study.

Optimal solution is in the statistic model field of the studied parameter, which has wide limits. To solve the problems with CAD systems every geometric and technical parameter should be determined exactly within the limits of the dimension range.

Expressing basic elements versus the main parameter of the studied machine is a necessary stage of drafting the technical design assignment. Soil, climatic and road conditions determine mathematical relationships of basic elements when designing a machine on the whole. Determining basic elements we find those geometrical and technical parameters and values which uniquely specify the main operational process and the core flow in order to visually and functionally distinguish from other similar objects of the system.

For such problems the best method to determine values of the basic elements is relying on a machine-reference sample in every standard dimension range. We take the dimensions as basic of that machine which has energy\output ration to the specific consumption of materials in the specified standard dimension range is minimal. As creating the machine image during developing technical requirements in CAD system is considered a creation of an interactive system then deviation of values of diagnostic variables from optimal is revealed in further iteration when determining parameters of operation convergency of the designed machine in the complex while operating in specific soil, climatic and road conditions. Iterating is done before receiving best values of the diagnostic variables of the basic elements in relation to generalized specific indicator $\frac{N_{уд}}{П_{туд}}$ in the dimension range.

To determine the limits of scraper dimension ranges we will rely on normative regulations in effect at the relevant time. These limits can be determined basing on the presented methodology of organizing fleet of earth moving machines with the account of operational conditions and reliability of the system according to efficiency function of the given costs per unit. But it was not a purpose of our work.

III. Results

In order to determine validity of the corresponding dependencies the following technological and linear-geometrical characteristics of scrapers for two-axile machines of soviet and foreign companies have been studied. The data for more than 127 sample machines and more than 1200 of their parameters and indexes have been studied.

The similarity relation

$$q=f(L, H, B, l) \quad (42)$$

correlates to the dependencies of real scrapers of different dimension ranges. But correlations:

$$q= f(b, D,A) \quad (43)$$

do not follow scaling laws and were determined by the statistical analysis method.

With this in mind, similarity coefficient values of the studied parameters with reference to the analysis of minimal values of generalized specific index $\frac{N_{уд}}{П_{туд}}$ for certain dimension ranges are in table 1.

TABLE I. SIMILARITY COEFFICIENT VALUES

Coefficient	less 4m^3	4-6m^3	6-8m^3	8-10m^3	10-15m^3	15-25m^3	more than 25м^3
CL	5.37	5.18	5.24	5.31	5.12	5.27	5.21
CW	1.42	1.49	1.43	1.52	1.51	1.46	1.48
CH	1.52	1.42	1.51	1.46	1.44	1.49	1.47
Cl	3.29	3.31	3.34	3.27	3.25	3.36	3.32
Cw	1.18	1.12	1.19	1.18	1.21	1.24	1.17
Ch	0.63	0.65	0.62	0.68	0.61	0.64	0.65
K_{l_1}	0.70	0.75	-	0.71	0.74	-	0.92
K_{l_2}	1.27	1.31	1.28	1.25	1.30	1.24	1.56
K_{B_1}	1.21	1.24	1.17	1.25	1.28	1.19	1.05
K_{B_2}	1.15	1.19	1.17	1.25	1.16	1.18	1.07
K_{D_n}	0.82	0.87	0.90	0.74	0.79	0.85	0.89
K_{D_3}	1.02	0.94	0.91	0.87	0.90	0.89	0.88
K_{A_n}	0.19	0.18	0.19	0.21	0.23	0.18	0.22
K_{A_3}	0.18	0.21	0.24	0.20	0.22	0.20	0.23

IV. CONCLUSION

To determine dependencies between technical and geometrical parameters of earth-moving machines in the structure of the complex system of mathematical economic models it is sensible to use mathematical relations, determining geometric image of the machine on the base of theory of similarity revealing the physical matter of the machine operation process. Such models can be effective in CAD systems at the stage of technical requirements designing. It has been found that utilization of the developed methodology for determining technical and geometric parameters of the machines versus operation conditions during combined action within the complex, related to the main parameter of the machine, allows determining at the stage of technical requirements specification the image of the designed machine with CAD systems. This methodology of developing a range of parameters for the machine scheme by determining similarity coefficient values basing on the analysis of the sample machine parameters of the given dimension range with the account of certain operational conditions can be used to receive an initial approximation image of some other earth-moving machines.

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