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A HYDRODYNAMIC TRANSMISSION SYNTHESYS OF AN EARTHMOVING MACHINE WITH PRESET TRACTIVE CHARACTERISTICS

Rosen MITREV

Abstract: *An algorithmic method for synthesis of hydrodynamic transmission parameters of an earthmoving machine with preset tractive characteristics is developed. An optimization task of four governing parameters is defined. An objective function is introduced that illustrates the deviation of the optimization generated tractive characteristics from the preset ones. Computer realization of the algorithmised method is carried out, by means of parameters of real machine are synthesized. The level of variation between the generated and the preset characteristics is evaluated.*

Key words: *synthesis, hydrodynamic transmission, earthmoving machine.*

1. PROBLEM DESCRIPTION

The synthesis of hydrodynamic transmission parameters of an earthmoving machine, with preset tractive characteristics, is a problem with ambiguous solution, due to the variety of possible transmission parameters combinations, leading to identical or closely related tractive characteristics.

In engineering practice, some elements parameters are determined under certain geometrical, design, power and other considerations. The rest, unknown parameters of the transmission, are determined according to the ones already set as well as in compliance with the known kinematical, power, geometrical and other dependencies, specific to the transmission and the preferred machine performance. Employing such a synthesis approach, for machines with preset tractive characteristics, leads to multiple design and computational iterations for different transmission parameters combinations.

If an algorithmic synthesis method of the hydrodynamic transmission parameters of earthmoving machines with preset tractive characteristics is available and computer related, then not only the determination of machine and transmission elements parameters is enhanced but the design process could be considerably speeded up as well.

2. SHORT LITERATURE SURVEY

A set of publications [1–4] are devoted to working out the tractive characteristics of earthmoving machines for certain transmission parameters. Among these, the studies, dealing with the synthesis of hydrodynamic transmission parameters of earthmoving machines, that meet some preset requirements, are relatively fewer. Study of the optimal work point of a diesel engine and torque converter is given in [5], while [6, 7] discuss the synthesis of hydrodynamic transmission parameters from viewpoint of fuel consumption requirements.

3. GOAL OF STUDY

The goal of this study is to create an algorithmic method for synthesis of hydrodynamic transmission parameters of earthmoving machines, with preset tractive characteristics and develop its computer implementation.

4. ALGORTHMIC METHOD FOR SYNTHESYS OF HYDRODYNAMIC TRANSMISSION PARAMETERS

The suggested method for synthesis of hydrodynamic transmission parameters of earthmoving machines is developed for machines of the most widespread scheme, namely, a torque converter connected in series to the transmission kinematics.

The basic steps of the algorithmic method are described in subtitles 4.1–4.4.

4.1. Analytical form of the preset tractive characteristics

Specific, preset tractive characteristics could be assigned to any earthmoving machine or standardized tractive class, according, mainly, to the preferred power, kinematical and technological possibilities of the particular machine or standardized tractive class of machines.

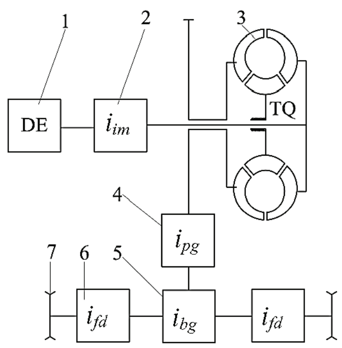


Fig. 1. Kinematics of a hydrodynamic transmission: 1) Diesel engine–DE; 2) intermediate gearbox with reduction ratio i_{im}; 4) torque converter-TQ; 4) planetary gearbox with variable reduction ratio i_{pg}; 5) main gear with reduction ratio i_{bg}; 6) final drive with reduction ratio i_{fd}; 7) driving wheel.

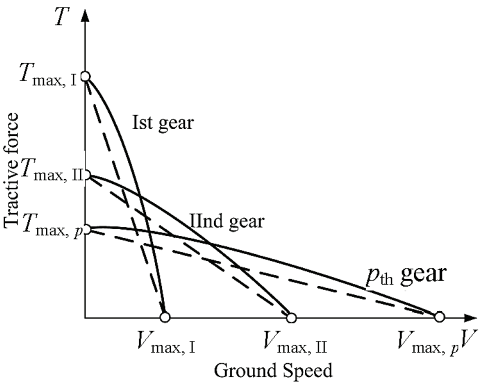


Fig. 2. Tractive characteristics of an earthmoving machine.

Tractive characteristics are represented by a function of $T_p(V_p)$ type, which is shown in Fig. 2, where T_p and V_p are tractive force and machine speed, respectively, at the p-th gear ratio, where p is the number of the current gear. Intersection points, between tractive characteristics and system axes, represent the maximal values of the tractive force $T_{\max.p}$ and machine speed $V_{\max.p}$ at the p-th gear.

Tractive characteristics, at the different gears $T_p(V_p)$, are associated with each other and for this reason, they are usually represented by the equation of the first gear tractive characteristics $T_I(V_I)$:

$$T_p(V_p) = f(T_I(V_I),\, p,\, q), \tag{1}$$

where q is the geometric series parameter of the planetary gearbox ratios.

The $T_p(V_p)$ characteristics could be represented by linear or higher order equations. In the case of a linear $T_p(V_p)$ relation, (1) reduces to:

$$T_p = \frac{1}{q^{2(p-1)}} \cdot \frac{T_{\max I}}{V_{\max I}} \cdot V_P + \frac{1}{q^{p-1}} \cdot T_{\max \cdot I}, \tag{2}$$

where

$$V_{\max\, p} = V_{\max\, I} \cdot q^{p-1}, \tag{4}$$

$$T_{\max\, p} = \frac{T_{\max I}}{q^{p-1}}. \tag{3}$$

Further, the synthesis will be performed by the tractive characteristics of the first gear $T_{\mathrm{I}}(V_{\mathrm{I}})$, while the rest of the gear ratios equations could be derived by (2). At this synthesis stage, the preset function (1) has a known analytical form.

4.2. Parametric reduction of the preset tractive characteristics to the turbine wheel shaft

Reduction of the preset tractive characteristic (linear force – linear velocity) to the turbine wheel shaft is performed by relations (5) and (6) – (torque-angular velocity):

$$M_T(\omega_{m.\kappa.},\, r_k,\, i_I) = \frac{(T_I(V_I) + P_f) r_k}{i_I \eta_I}, \tag{5}$$

$$\omega_{m\kappa}(r_k,\, i_I) = \frac{V_I i_I}{r_k}, \tag{6}$$

where P_f is road resistance; r_k – radius of the driving wheel; i_I, η_I – overall reduction ratio and coefficient of efficiency of the transmission kinematics after the TQ at the first gear. The following equation is valid:

$$i_I = i_{fd} \cdot i_{bg} \cdot i_{I\,pg}. \tag{7}$$

In the case of linear equation (1), relation (5) has the following form:

$$M(\omega_{tw.},\, r_k,\, i_I) = A\omega_{tw} + B, \tag{8}$$

$$A = -\frac{T_{\max I}}{V_{\max I} . \eta_I} \cdot \left(\frac{r_k}{i_I}\right)^2; \quad B = \left(T_{\max I} + P\right) \cdot \frac{r_k}{i_I \cdot \eta_I}. \tag{9}$$

At this synthesis stage, the parameters r_k and i_{I} are unknown.

4.3. Parametric output characteristics of the "DE-TQ" system

4.3.1. Analytical form of the DE performance map

The DE is chosen by certain considerations [5]. DE performance map represents the torque at the crankshaft versus angular velocity at the different throttle openings. An appropriate analytical representation is achieved by experimental discrete values and interpolation between them or by polynomial approximation.

4.3.2. Analytical form of the TQ characteristics

The TQ dimensionless characteristics is represented by the analytical relations of capacity factor $\lambda(i_{\mathrm{TQ}})$, torque ratio $\mathrm{K}(i_{\mathrm{TQ}})$ and the efficiency $\eta(i_{\mathrm{TQ}})$, where i_{TQ} denotes the speed ratio of the TQ. The pumping wheel torque is represented by the following equation:

$$M_{pw} = \lambda(i_{TQ}) \cdot \rho \cdot D^5 \cdot \omega_{pw}(\omega_{DE},\, i_{im})^2, \tag{10}$$

where $\omega_{pw}(\omega_{\mathrm{DE}},\, i_{im})$ is angular velocity of the pumping wheel; D is the active diameter of the pumping wheel, ρ is the density of working fluid. The following equation is valid as well:

$$\omega_{pw}(\omega_{DE},\, i_{im}) = \frac{\omega_{DE}}{i_{im}}. \tag{11}$$

At this synthesis stage, parameters D and i_{im} are unknown.

4.3.3. Analytical determination of the "DE-TQ" system work points

The "DE-TQ" system work points are obtained by solving the nonlinear algebraic equation (12) for different values of i_{TQ} within the interval 0 to 1 with a step value of Δi_{TQ}:

$$M_{DE}(\omega_{DE}) i_{im} \eta_{im} = M_{pw}(i_{TQ}, \omega_{pw}, D, \omega_{DE}, i_{im}). \tag{12}$$

The solutions $\omega_0(i_{TQ},\, D,\, i_{im})$ of (12) are the "DE-TQ" system work points and they are functions of the unknown parameters D and i_{im}.

4.3.4. Drawing the "DE-TQ" system output characteristics

The output characteristics $M_{tw}(\omega_{tw})$ of the "DE-TQ" system includes relations (13) and (14).

$$\omega_{tw}(i_{TQ}, i_{im}, D) = \omega_o(i_{TQ}, D, i_{im}) \cdot i_{TQ}, \qquad (13)$$

$$M_{мк}(i_{xm}, i_{cp}, D) = M_{пк}(i_{xm}, \omega_o) \cdot K(i_{xm}), \qquad (14)$$

where M_{pw} and ω_{pw} are torque and angular velocity, respectively, of the TQ turbine wheel.

4.4. Definition of the optimization task

The parameter synthesis of a hydrodynamic transmission of an earthmoving machine, with preset tractive characteristics is reduced to the determination of the hydrodynamic transmission parameter values that will minimize differences between (14) and (5).

In fact, a nonlinear multi-parametrical optimization task is at hand, utilizing the following vector of governing parameters:

$$\{U\} = \{i_{im}, D, r_k, i_I\}. \qquad (15)$$

4.4.1. Objective function definition

We suggest to work out the objective function employing the least squares of the differences between (14) and (5) and seek its minimization.

$$\text{SERR}= \sum_{i_{xm}=0}^{1} (M_T(\omega_{tw.}, r_k, i_I) - M_{tw}(i_{TQ}, i_{im}, D))^2. \quad (16)$$

4.4.2. Constraints

The optimization constraints are imposed taking into account corresponding design considerations. The parametric constraints are:

$$\begin{aligned} &i_{cp\,\min} \le i_{cp} \le i_{cp\,\max}, \quad D_{\min} \le D \le D_{\max}, \\ &r_{k\,\min} \le r_k \le r_{k\,\max}, \quad i_{I\,\min} \le i_I \le i_{I\,\max}. \end{aligned} \qquad (17)$$

The minimal differences between intersection points of generated tractive characteristics and system axes and intersection points of preset tractive characteristics and system axes are ensured by the next functional constraints:

$$\begin{aligned} &\Delta M_{l\,\min} \le M_{tw}(0, i_{im}, D) - M_T(\omega_{tw}, r_k, i) \le \Delta M_{l\,\max}, \\ &\Delta M_{r\,\min} \le M_{tw}(1, i_{im}, D) - M_T(\omega_{tw}, r_k, i) \le \Delta M_{r\,\max}, \end{aligned} \qquad (18)$$

where $M_{l.\min}$, $M_{l.\max}$, $M_{r.\min}$, $M_{r.\max}$ are the minimum and the maximum permissible differences between preset and generated tractive characteristics at the intersection points with system axes.

5. COMPUTER IMPLEMENTATION AND NUMERICAL EXAMPLE

The suggested method is realized in a general purpose computer algebra system. The numerical optimization is performed by quasinewtonian method.

Parameter synthesis is illustrated for an industrial wheel bulldozer. The following data is used:

$$T_{\max I} = 330 \text{ kN}; \; V_{\max I} = 1.95 \text{ m/s};$$

$$\eta_I = 0.8; \; \eta_{im} = 0.95; D_{\max} = 0.6 \text{ m};$$

$$P_f = 13.5 \text{ kN}; \; \rho = 850 \text{ kg/m}^3; \; i_{im\,\min} = 0.6;$$

$$i_{im\,\max} = 2; \; r_{k\,\min} = 0.2 \text{ m}; \; r_{k\,\max} = 2 \text{ m}; D_{\min} = 0.2 \text{ m};$$

$$i_{I\,\min} = 50; \; i_{I\,\max} = 150; \; \Delta M_{l\,\min} = \Delta M_{r\,\min} = -10 \text{ Nm}$$

$$\Delta M_{l\,\max} = \Delta M_{r\,\max} = 10 \text{ Nm}; \; p = 4, \; q = 1.71.$$

Fig. 3a shows the DE map, while Fig. 3b shows the dimensionless TQ characteristics.

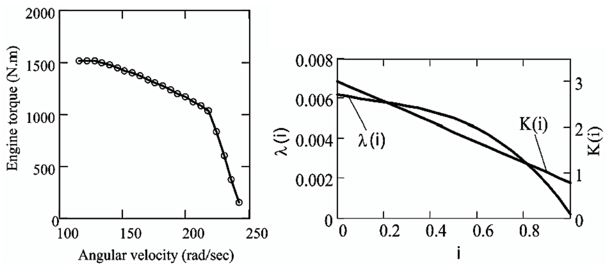
The preset tractive characteristics are linear and the corresponding analytical form is derived by means of (2). After completion of the numeric optimization, the following is obtained:

$$i_{im\,opt} = 0.6, \; D_{opt} = 0.262 \text{ m}, \; r_{k\,opt} = 0.51 \text{m}, \; i_{I\,opt} = 102.$$

The value of the objective function (16) is $9.25 \cdot 10^3$.

Fig. 4 shows the preset tractive characteristics as well as those, generated at the acquired optimal values of design parameters while Fig. 5 presents the deviations between them at different gear ratios. The values proximity is obvious and the maximum error is about 3%. The objective function graph is plotted in Fig. 6 where r_k and i_I are fixed.

Special attention is given to the case, where $i_{im} = 1$ (direct connection between DE and TQ) and r_k = const (radius of driving wheels is chosen by other considerations), in our case $r_k = 0.7$ m. In this case we have two governing parameters – D and i_I. As a result of the numeric optimization, the following is obtained: $D_{opt} = 0.356$ m, $i_{im\,opt} = 92$. The objective function value is $2.68 \cdot 10^4$.



a) b)

Fig. 3. a) DE map; b) dimensionless TQ characteristics.

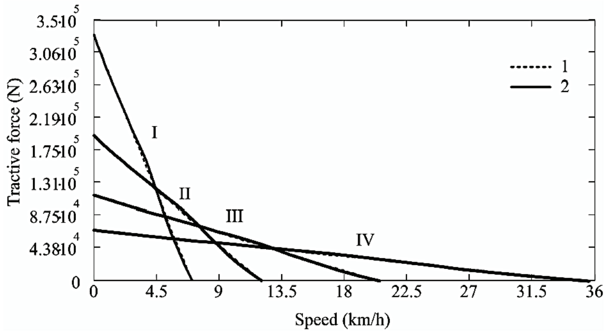


Fig. 4. Preset 1 and generated 2 tractive characteristics at the optimal values of design parameters.

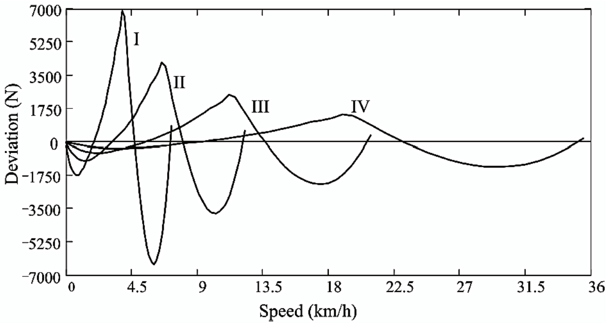


Fig. 5. Deviation between preset and generated tractive characteristics at different gear ratios.

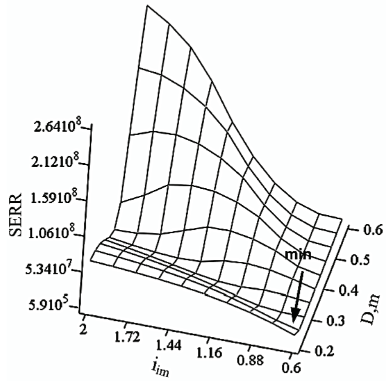


Fig. 6. Graphics of the objective function SERR.

6. CONCLUSIONS

On the basis of the performed theoretical and numerical investigations, the following basic conclusions could be drawn:

A method for parametric synthesis of an earthmoving machine with hydrodynamic transmissions and preset tractive characteristics is introduced;

The performed numerical optimization and comparison between the obtained and real machine parameters prove, that the method presented is suitable for the synthesis of hydrodynamic transmission parameters;

After appropriate transformations, the introduced method could be used for the parametric synthesis of other transmission types.

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Author:

Rosen MITREV, Ph.D., assistant professor, Technical University – Sofia, Bulgaria, Department “Engineering logistics, material handling and construction machines”,
E-mail: `rosenm@tu-sofia.bg`