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SELECTION OF THE OPTIMAL TWO STAGE PLANETARY GEAR TRAIN FOR APPLICATION AT SLEWING PLATFORM DRIVE MECHANISM OF HYDRAULIC EXCAVATOR

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Abstract

The objective of this study is the application of multicriteria optimization to a planetary gear train predicted for use at slewing platform drive mechanism of hydraulic excavator. Based on the conditions under which transmission works, two stage planetary gear train consist of basic type of planetary gear trains is considered. A model of planetary gear multicriteria optimization based on an original algorithm implemented in the PlanGears software is used for that purpose. The basis for the algorithm is approximations of analytical expressions for volume, mass, efficiency and production costs. The following is adopted as optimization variables: numbers of teeth, number of satellites, module and facewidth. Conditions required for the proper functioning of the system regarding geometry and strength are expressed by the functional constraints.

Key words*: optimal solution, planetary gear train, slewing platform drive mechanism*

1 INTRODUCTION

Recently, planetary gear trains (PGTs) have found an ever-expanding area of industrial applications, due to their advantages, the most notable being a compact design and the beneficial effect of power being split over several planet gears. This enables the design of PGTs with high power ratings combined with a wide range of transmission ratios. On the other side, a large diversity of kinematic schemes and the need for relatively complex calculations in comparison to conventional gearboxes, means that systematic research must be undertaken to realize the full potential of planetary gearboxes.

This paper provides the application of multicriteria optimization to a planetary gear train predicted for use at slewing platform drive mechanism of hydraulic excavator. Based on the conditions under which transmission works, two stage planetary gear train consist of basic type of planetary gear train is considered. A model of planetary gear multicriteria optimization based on an original algorithm implemented in the *PlanGears* software is used for that purpose

2 SLEWING PLATFORM DRIVE MECHANISM

The primary function of the manipulator of hydraulic excavators is enable active work tools on the subject of work in a particular working area of machines. Manipulators of hydraulic excavators represent a transmission of the kinematic chain machine that connects the support and movement mechanism member with executive members - machine tools. Depending on the shape of the work area, kinematic chain of manipulators can be planar or spatial configuration. Spatial manipulators provide the necessary spatial manipulation of machine. Spatial working area is usually achieved with the first member link - slewing platform and support and movement mechanism, using a slewing joint in the form of an axial bearing with a vertical axis relative to the support surface of machine. Relying on the surface the support and movement mechanism is relatively stationary member relative to a slewing platform that can realize unlimited range of rotation in both directions around vertical axis of the joint.

The general design of the slewing platform drive comprises (Fig. 1): hydraulic motor 1 driven by hydraulic pump, reducer 2 and axial bearing 3. In principle, drive components of slewing platform create planetary mechanism where the rotation of the output gear reducer *2.1*, with angular velocity, as satellites and the drive member, also turns slewing platform L_2, with angular velocity, as a carrier of the satellite (reducer), whereby the ring gear *3.1* of bearing as a central gear and stationary because it is attached to the support and movement mechanism of machine [1].

It is characteristic that the hydraulic motor and the reducer form an intergrated transmission, where separate modules are produced by specialized manufacturers, with very different parameters for all sizes of excavators and other mobile machines. The wide availability of integrated transmissions, in excavator design, offers the ability to synthesise possible variants of the slewing platform drive with a lower specific flow of the hydraulic motor and a higher transmission ratio of the reducer and vice versa.

In order to make decission related to transmission choice, the selection of optimal transmission according to main criteria is done.

One of the leaders in integrated transmissions manufacturing is Rexroth MOBILEX. The Drive Control Company Rexroth MOBILEX are delivered planetary gearboxes ready for installation, but without oil filling.

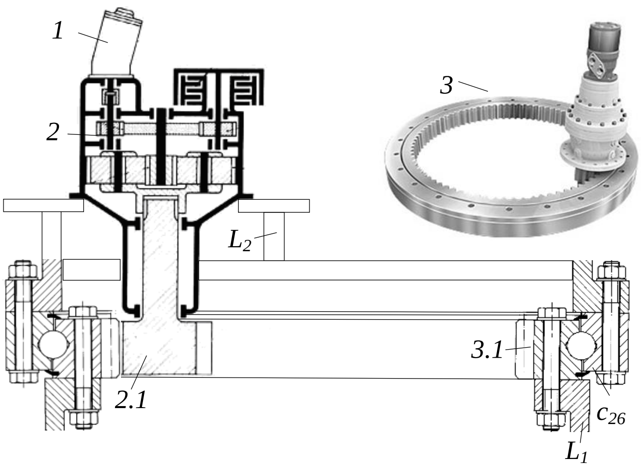

Fig. 1 *Slewing platforms drive mechanism of hydraulic excavator*

Transmissions are defined by output torque, gear ratio, output speed for the selected integrated transmission for application at slewing platform drive mechanism. In the Fig. 2 two-stage compact drive is given [1,2]. The customer specifications for swing drives is pointed in the data catalog [2].

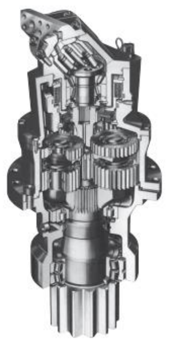

Fig. 2 *Rexroth MOBILEX GFB two-stage hydrostatic compact drive with a multiplate parking device and a Rexroth plug-in motor*

The intention in this paper is to determine the design parameters of the planetary gear train stages, by using the software PlanGears, according to multicriteria optimization. The input data is defined according the data from Rexroth MOBILEX catalog. In this way it is possible to check the program accuracy and possibility.

3 STRUCTURES OF BASIC TYPE OF PGT

Two stage transmission shown in the Fig. 1 consists of basic type of planetary gear train which is given in the Fig. 3.

The basic type of a planetary gear train (PGT), i.e. a design which has a central sun gear (external gearing - 1), central ring gear (internal gearing - 3), satellites (planets - 2) and carrier (h), shown in Fig.31, is the subject of the paper, limited to geared pairs. Planets are in simultaneous contact with the sun gear and the ring gear.

This type of a PGT is often used as single stage transmission, as a building block for higher compound planetary gear trains.

Its advantage over other PGT types lies, first of all, in its efficiency. The efficiency value varies negligibly in the whole range of the internal gear ratio ($p = |z_3| / z_1$). Also, this type has small overall dimensions and mass, and its production costs are relatively low because of the relatively simplified production.

Because of its characteristics, it is applicable in transport and stationary machines without limitation in power and velocity.

It is appropriate to show a basic planetary gear train with the Wolf-Arnaudov's symbol, Fig. 3c [3,4].

By using this symbol the train shafts are shown with different width lines and a circle. Sun gear shaft 1 is shown by a thin line, ring gear shaft 3 by a thick line and the carrier shaft *h* by two parallel lines since the carrier shaft is summary element regarding by carrier stopping negative transmission ratio is obtained.

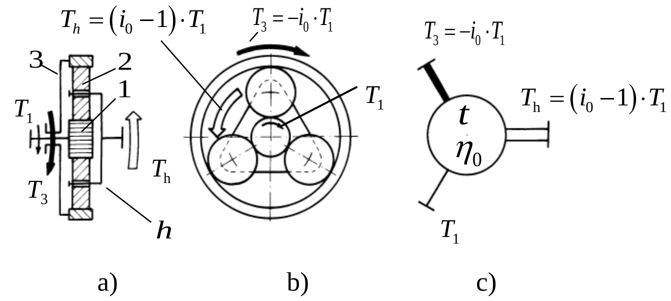

Fig. 3 *Wolf-Arnandov's symbol and torque ratios of the basic type of PGT*

Planetary gear train shafts are loaded with torques whose ratio is also shown in Fig. 3. Torques on the ring gear shaft T_3 and on the carrier shaft T_h are given as a function of the ideal torque ratio *t* and the torque on the sun gear shaft T_1 [5,6].

Ideal torque ratio:

$$t = \frac{T_3}{T_1} = \frac{T_{Dmax}}{T_{Dmin} = \frac{|z_3|}{z_1} > +1}$$

Torques:

$$T_1 : T_3 : T_S = +1 : +t : -(1 + t)$$

It is assumed:

$$\eta_0 = \eta_{13(h)} = \eta_{31(h)} = 1$$

4 MATHEMATICAL MODEL FOR PGT OPTIMIZATION

The process of finding the optimal solution starts by defining a mathematical model [7].

An optimization task is defined by the variables, objective functions and conditions required for the proper functioning of a system determined by the functional constraints.

The complete procedure of optimal solution selection is described in [7,8,9], and now will be briefly pointed. Under the mathematical model definition, it is necessary to determine the objective functions, functional constraints and variables since each objective function is the function of several parameters. The following characteristics are chosen for objective functions of a planetary gear train: volume, mass, efficiency and production cost of gear pairs.

$$V = \frac{\pi}{4} \cdot b \cdot \left(\frac{m_n \cdot z_3}{\cos\beta} \cdot \frac{\cos\alpha_t}{\cos\alpha_{wt23}} \right)^2 \quad (1)$$

$$\boldsymbol{m = 0.25 \cdot \pi \cdot b \cdot \rho \cdot \frac{m_n^2}{cos^2\,\beta} \cdot \Big[k_1 \cdot z_1^2 \cdot \frac{cos^2\,\alpha_t}{cos^2\,\alpha_{wt12}} +} \\ \boldsymbol{+ n_w \cdot k_2 \cdot z_2^2 \cdot \frac{cos^2\,\alpha_t}{cos^2\,\alpha_{wt12}} + k_3 \cdot z_3^2 \cdot \frac{cos^2\,\alpha_t}{cos^2\,\alpha_{wt23}} \Big]} \quad (2)$$

$$\eta = \frac{1 - i_0 \cdot \eta_0}{1 - \eta_0} \quad (3)$$

$$F_T = T_{P1} + n_w \cdot T_{P2} + T_{P3} \quad (4)$$

Then, mathematical model of nonlinear multi-criteria problem in concrete task, can be formulated as follows:

$$max\{f_1(x), f_2(x), f_3(x), f_4(x)\} \text{ subject to } x \in S \quad (5)$$

where:

$$f_1(x) = -V(x), f_2(x) = -m(x), \\ f_3(x) = \eta(x), f_4(x) = -T(x)$$

The most important criterion for selecting these "equally good" solutions is the *Pareto optimality concept*: Solution $x \epsilon S$ is Pareto optimal if there is no solution $y \epsilon S$ such that holds $f_i(x) \leq f_i(y)$ for all $i=1,......,n$ and for at least one index i holds strict inequality, i.e. $f_i(x) < f_i(y)$. Determination of the Pareto optimal solutions set is the first step in optimal solution finding. Next step is optimal solution choice from Pareto set. In this model weighted coefficients method is applied for choosing optimal solution from Pareto solutions [7,8].

Thus, some additional information is needed in order to be able to select one of the solutions as the final solution. This final decision is made by a corresponding *scalarized problem*.

In this method the following scalarized problem is constructed:

$$max\, f^M(x) = w_1 f_1^0(x) + \cdots + w_m f_m^0(x) \quad \text{s.t. } x \in S \quad (6)$$

Here, the weighted coefficients (or weights) w_i are positive real numbers and $f_i^0(x) = (f_i^0)^{-1} f_i(x)$ are normalized objective functions where f_i^0 are normalizing coefficients. In this approach, the components of the ideal point $f^* = (f_1^*, f_2^*, f_3^*, f_4^*)$ are used as normalizing coefficients, i.e. $f_i^0 = f_i^*$ for $i = 1,2,3,4$.

Therefore, absolute values of all objective functions are between 0 and 1, which simplifies the choice of the weighted coefficients. All solutions obtained by this method are Pareto optimal.

In this paper, the following variables are considered: the number of teeth of the central sun gear z_1, the number of teeth of planets z_2, the number of teeth of the ring gear z_3, the number of satellites n_w, the gear module m_n and the facewidth b. Functional constraints are related to mounting conditions, geometrical conditions and strength conditions.

Optimization procedure

For the given input data (input number of revolution, input torque, service life in hours, application factor, accuracy grade (Q-DIN3961), minimal safety factor - flank, minimal safety factor - root, gear materials, allowed deviation of gear ratio, range of z_1 variation), all 6-tuples of design parameters $(z_1, z_2, z_3, n_w, m_n, b)$ satisfying the functional constraints are generated and the values of the objective functions for every 6-tuple are computed (marked with a capital letter "A" and number). A set of feasible solutions is obtained. Than, the set of Pareto solutions is created.

Next, it is necessary to choose only one optimal solution among all the generated solutions. The weighted coefficient method for solving multicriteria optimization problem is predicted.

5 NUMERICAL EXAMPLE

The input data for optimal design parameters choice is adopted according to data in [1,2].

The first stage

The next input data is chosen for the multi-criteria optimization application: i=5.57, n_{in}=2061.409 min^{-1}, T_{in}=309.387 Nm, L=5000h, IT7 for all gears, sun gear material/satellite material/ring gear material are 20MnCr4/20MnCr4/34CrNiMo6, S_{Hmin}=1.1, S_{Fmin}=1.2, Δi=3%, z_1=12÷26 . The feasible set consists of 6830 solutions. The number of Pareto solutions is 114. Since the transmission is predicted for use in the hydraulic excalator, the space for transmision to be set up is not special demand. By application weighted coefficient method with weighted coefficient: w_1=0.0, w_2=0.0, w_3=0.5, w_4=0.5 where the equal priority is assigned to efficiency and production costs, the solution shown in Table 1 is obtained, with a set of objective functions values shown in Table 2.

Table 1 Optimal solution for first stage obtained by weighted coefficient method

Variable values					
$x_1=z_1$	$x_2=z_2$	$x_3=z_3$	$x_4=n_w$	$x_5=m_n$	$x_6=b$
29	49	-130	3	2	26

Table 2 Objective function for solution shown in table 1

f_1 [mm^3]	f_2 [kg]	f_3	f_4 [min]
1346541, 868	6.45	0.99	165.054

The second stage

Since the output of the first stage is the input of the second stage, the next input data is chosen for the multi-criteria optimization application: i=5.63, n_{in}=370.091min^{-1}, T_{in}=1706.014 Nm, L=5000h, IT7 for all gears, sun gear material/satellite material/ring gear material are 20MnCr4/20MnCr4/34CrNiMo6, S_{Hmin}=1.1, S_{Fmin}=1.2, Δi=3%, z_1=12÷26.

The feasible set consists of 11059 feasible solutions. The number of Pareto solutions is 117. By application weighted coefficient method with weighted coefficient: w_1=0, w_2=0,

w_3=0.5, w_4=0.5 the solution shown in Table 3 is obtained, with a set of objective functions values shown in Table 4.

Table 3 Optimal solution for second stage obtained by weighted coefficient method

Variable values					
$x_1=z_1$	$x_2=z_2$	$x_3=z_3$	$x_4=n_w$	$x_5=m_n$	$x_6=b$
34	61	-158	3	2.75	44

Table 4 Objective function for solution shown in table 3

f_1 [mm^3]	f_2 [kg]	f_3	f_4 [min]
6487487.53	30.3	0.99	296.96

It can be concluded that this design parameters of planetary gear trains in the both stages satisfy requirements defined in the input data. Since one of the criteria is efficiency, and efficincy according to (3) depends on the teeth numbers of gear, the solution with great number of teeth is chosen.
Since the efficiency value varies negligibly in the whole range of internal gear ratio, it is possible to consider other solutions without prioritizing any objective function. If all objective functions are taken into consideration with equal weights, the solutions for the both stages are shown in the table 5 and table 7 with objective functions in the table 6 and table 8. This two-stage transmission variant is applicable too, since the efficiency has high value and other objectie functions have values which satisfy the other demands.

Table 5 Optimal solution for second stage obtained by weighted coefficient method

Variable values					
$x_1=z_1$	$x_2=z_2$	$x_3=z_3$	$x_4=n_w$	$x_5=m_n$	$x_6=b$
24	43	-111	3	2	23

Table 6 Objective function for solution shown in table 5

f_1 [mm^3]	f_2 [kg]	f_3	f_4 [min]
890273.95	4.22	0.989	140.276

Table 7 Optimal solution for second stage obtained by weighted coefficient method

Variable values					
$x_1=z_1$	$x_2=z_2$	$x_3=z_3$	$x_4=n_w$	$x_5=m_n$	$x_6=b$
25	44	-115	4	3	38

Table 8 Objective function for solution shown in table 3

f_1 [mm^3]	f_2 [kg]	f_3	f_4 [min]
3519039.83	18.921	0.989.99	262.22

In the second case, since there are the smaller values for the number of teeth of all gears, it is possible to obtained smaller and more compact housing, with great value for efficincy.
Giving different priority to the objective function, the other solution would be obtained.

6 CONCLUSION

In this paper, an original model for multi-criteria optimization to the two stage planetary gear trains for application at drive mechanism of hydraulic excavator is presented These compound gear trains consist of two basic type of planetary gear trains. The optimal solutions are obtained for the both transmission ratios. The weight coefficient method is used for choosing the optimal solution from the Pareto optimal set. Two choices are presented: with equal weights and with consederation only two objective functions.The results obtained in these way are in accordance with the literature on technical system optimization and indicate a good choice of the applied methods.

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