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JUSTIFICATION OF EFFICIENCY OF EPICYCLICAL GEAR TRAIN
IN DEVICE FOR SPEED CHANGES MANAGEMENT

Received: February 9, 2017 / Revised: March 22, 2017 / Accepted: June 26, 2017

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Abstract. The article analyses the functioning of epicyclical gear train with closed circuit hydrosystem, where the driving element is the sun gear and driven one is the carrier or vice versa. Control element is the ring gear, which rotates or can be stopped by the closed circuit hydrosystem.

We have conducted a theoretical research of efficiency in such epicyclical gear train. Using the means of computer modelling, we have obtained graphical dependences of the transmission efficiency from its parameters.

The analytical and graphical dependences have been obtained allow visually verifying the change of efficiency value and evaluating it in terms of self-braking.

Keywords: efficiency, epicyclical gear train, speed change management, closed circuit hydrosystem, sun gear, driven gear, ring gear, transmission.

Introduction

Functioning of hoisting, building, road and land reclamation machines, cars and tractors, machine tools and other equipment requires the speed changes management of executive mechanisms for different processes. In the world of technology, there are widely known methods and devices for speed management that provide stepped or continuously variable change in velocity by the value and direction with the use of respective gearboxes. However, these methods have many shortcomings.

Problem statement

The main disadvantages of stepped speed management devices are the complexity of design, their large material consumption, the emergence of dynamic loads during the transition from one speed to another, even in case of synchromesh using. On the other hand, continuously variable speed devices have intense components wear due to the use of friction connections like brakes or lock-up clutches. All abovementioned reduces the durability and reliability of certain device components and machine in general.

Analysis of modern information sources on the subject of the article

Some world technical literature [1]–[16] suggests the new method of speed changes management by single or multi-row epicyclic gear trains combined with closed circuit hydrosystem. Reports of conferences and other scientific discussions, for example, [17]–[21], often draws attention to the efficiency of such patented [22]–[25] devices for speed changes management and highlight the need of further theoretical studies of their kinematics, power and geometrical parameters.

General concepts of efficiency coefficient are widely described in well-known classical technical literature on theory of mechanisms and machines, for example, [26] but it slightly concerns the specific cases of specific mechanisms.

Statement of purpose and tasks of research

The purpose of this research is to perform theoretical and computer analysis of the efficiency value for speed changes management devices in form of epicyclic gear train with closed circuit hydrosystem when the driving element is the sun gear, and the driven is carrier, or vice versa. Speed management is
being performed by ring gear, which through the gearing rotates hydraulic pump that is pumping fluid in the case when the following condition is true: $\omega_1 = 0...\omega_{3\text{max}}$.

**Main material presentation**

It is well known that the efficiency estimates the excellence of machinery and mechanisms and is an object of constant improvement. Efficiency lies within $0 \leq \eta < 1$ and is a value that is determined by the ratio of useful and consumed energy by known formulas. It can be written as

$$\eta = \frac{P_{kc}}{P_n}, \quad (1)$$

where $P_{kc}$ is power of useful forces; $P_n = P_{kc} + P_{uc}$ is total power supplied to the mechanism; $P_{uc}$ is power of harmful forces.

The abovementioned general definition of efficiency can be specified for individual cases and, importantly, you can get the formula to determine it via other mechanisms parameters.

It is not always necessary to determine the efficiency of epicyclic gears. If it is used as a reduction gearbox that transmits power to machine actuator for extended periods, then, for clarification of its suitability the efficiency should be determined. When we use epicyclic gearing as a speed control device the determination of efficiency may not be important if there is a solid confidence that the transmission is not self-braking.

There are three popular practical methods of efficiency determining [26], which can be taken as the base for solving specific tasks set.

The efficiency of suggested device for speed changes management by epicyclic gear train with closed circuit hydrosystem, where the driving element is the sun gear, driven is a carrier and managing ring gear, initially can be given as follows

$$\eta = \eta_{14} \eta_6 \eta_7, \quad (2)$$

where $\eta_{14}$ is efficiency of epicyclical gear train; $\eta_6$ is efficiency of hydrosystem gear drive; $\eta_7$ is efficiency of closed circuit hydrosystem (power loss to pump operation when pumping fluid in a closed circuit hydrosystem).

**Fig. 1.** Block diagram of possible power losses in the device for speed changes management by epicyclical gear train with closed circuit hydrosystem, where the driving element is the sun gear, driven gear is a carrier and managing element is ring gear

The analysis of power losses in the device (Fig.1) implies that some of the power inputted on the sun gear goes to the carrier via satellite, and the other goes to the ring gear and closed circuit hydrosystem.
To determine the efficiency let us consider the forces acting in gearing of sun gear and satellite \( F_{12} \), satellite and ring gear \( F_{23} \), satellite and carrier \( F_{24} \) and write the equilibrium condition for satellite (Fig. 2) as

\[ F_{12} + F_{23} + F_{24} = 0. \]  

Furthermore, the sum of the moments of forces acting on the satellite, relative to the axis of its rotation is equal to zero:

\[ F_{12}r_2 + F_{23}r_2 = 0, \]  

where \( r_2 \) is the radius of the initial circle of satellite, with the number of teeth \( z_2 \).

From the expressions (3) and (4) the forces acting on the epicyclical gear train elements will be:

\[ F_{12} = -F_{23}; \]  
\[ F_{24} = -(F_{12} + F_{23}). \]  

The formulas obtained show that one of given forces makes it possible to determine other two.

If torque \( T_1 \) is set, then

\[ F_{12} = T_1 / \eta_1, \]  

where \( \eta_1 \) is the radius of the initial circle of sun gear \( z_1 \).

According to (7), when the torque applied to the ring gear in fixed carrier train, we will have

\[ T_3 = F_{23}r_3 = -\frac{\eta_1}{\eta_1}T_1 = -u_{13}^{(4)}T_1, \]  

i.e., torques \( T_1 \) and \( T_3 \), excluding friction, relates the same way as in gearing with fixed axles. Considering the friction on the tooth, the relationship between torques can be represented as

\[ T_3 = -T_1u_{13}^{(4)} \eta_1^k, \]  

where \( \eta_{13} \) is efficiency for the gearing with fixed axles, defined as for sequential gearing; \( k = +1 \) when the power transmitted from gear \( z_1 \) to gear \( z_3 \) and \( k = -1 \) in opposite case; \( u_{13}^{(4)} = -z_3 / z_1 \) is fixed carrier train ratio.

In this case, we have to determine efficiency of epicyclic train because it transfers significant power from the sun gear to the carrier or vice versa, i.e. it is used as power transmission, and epicycle is a speed control element.

**Fig. 2.** Scheme of single-row epicyclical gear train: 1 – sun gear; 2 – satellite; 3 – ring gear; 4 – carrier; 5 – frame; 6 – gearing; 7 – closed circuit hydrosystem
The relationship between torques acting on the elements of the epicyclic train can be established with consideration of equilibrium conditions of transmission in general, namely:

\[ T_1 + T_3 + T_4 = 0, \]  \hspace{1cm} (10)

where \( T_4 \) is torques acting on the carrier. According to [26]

\[ T_4 = -T_1(1 - u_{13}^{(4)}k_{13}). \]  \hspace{1cm} (11)

When the driving element is the sun gear and the driven - carrier, i.e. the resistance torque applied to the carrier, then the expression for efficiency will be as follows

\[ \eta_{14} = -\frac{T_4\omega_4}{T_1\omega_1 + T_3\omega_3}. \]  \hspace{1cm} (12)

Substituting values \( T_1, T_3 \) and \( T_4 \) in (12) and express \( \omega_4 \) through \( \omega_1 \) using the formula (2) [6], after simple transformations, we get:

\[ \eta_{14} = \frac{(1 + u_{13}^{(4)}k_{13})(\omega_1 + \omega_3u_{13}^{(4)})}{(1 + u_{13}^{(4)}k_{13})(\omega_1 + \omega_3u_{13}^{(4)}k_{13})}. \]  \hspace{1cm} (13)

In order to show the nature of the efficiency change in epicyclic train with a closed circuit hydrosystem, when the sun gear is driving element and the carrier – driven, from the parameters of transmission more clearly we have performed next. Equation (13) has been programmed and we got the computer graphics dependence \( \eta_{14} = f\left(\omega_1, \omega_3, u_{13}^{(4)}\right) \) for gear ratios \( u_{13}^{(4)} = 1...10 \), the angular velocity of driving element \( \omega_1 = 100 \text{ rad/s} \). Graphic dependences obtained for \( \omega_3 = 0...40 \text{ rad/s} \), \( k_{13}^{(4)} = 0,97 \) are shown in Fig. 3.

![Graph showing efficiency changes](http://ena.lp.edu.ua)

**Fig. 3.** Graphic dependences of efficiency changes in single-row epicyclical gear train when the driving element is the sun gear and the driven – carrier, depending on the gear ratio \( u_{13}^{(4)} \) and speed of control element \( \omega_3 \).
The efficiency of device for speed changes management by epicyclical gear train with closed circuit hydrosystem, where the driving element is the carrier, driven is a sun gear and managing ring gear, initially can be given as follows

\[ \eta = \eta_4 \eta_6 \eta_7, \]  

(14)

where \( \eta_4 \) is efficiency of epicyclical gear train; \( \eta_6 \) is efficiency of hydrosystem gear drive; \( \eta_7 \) is efficiency of closed circuit hydrosystem (power loss to pump operation when pumping fluid in a closed circuit hydrosystem).

Block diagram of possible power losses in the device for speed changes management by epicyclical gear train with closed circuit hydrosystem, where the driving element is the carrier, driven is a sun gear and managing ring gear, is shown in Fig. 4.

**Fig. 4.** Block diagram of possible power losses in the device for speed changes management by epicyclical gear train with closed circuit hydrosystem, where the driving element is the sun gear, driven is a carrier and managing element is ring gear

If the torque \( T_1 \) is a moment of resistance of the working machine – sun gear is driven, \( T_4 \) is the torque of the driving element – carrier, \( T_3 \) is a torque of control element – ring gear, then the efficiency can be put as the ratio of useful power to full power

\[ \eta_{41} = -\frac{T_1 \omega_1}{T_4 \omega_4 + T_3 \omega_3}. \]  

(15)

When we substitute the values \( T_1, T_3 = -T_{41} u_{13}^{(4)} \eta_{13} \) and \( T_4 = -T_1 (1 - u_{13}^{(4)} \eta_{13}^{-1}) \) in the formula (15) with the ones from (9) and (11) and replace \( \omega_1 \) with \( \omega_4 \) by using the formula (3) [8], after simple transformations, the expression for efficiency of the train with driven sun gear will be

\[ \eta_{41} = \frac{[\omega_4 (1 + u_{13}^{(4)}) - \omega_3 u_{13}^{(4)} \eta_{13}]}{\omega_4 (\eta_{13} + u_{13}^{(4)}) - \omega_3 u_{13}^{(4)}}. \]  

(16)

Similarly to the previous case, we obtained graphics from expression (16) for the next initial data:

\( \eta_{13}^{(4)} = 0.97; \omega_4 = 100 \) rad/s; \( u_{13}^{(4)} = 1...10 \) and \( \omega_3 = 0...80 \) rad/s, and they shown in Fig. 5.

For the two-row epicyclic gear train, shown in Fig. 6, the conclusions are similar and differ only in the value of gear ratio \( u_{13}^{(4)} \), which now equal to:

\[ u_{13}^{(4)} = -\frac{z_2 z_3}{z_1 z_2}. \]  

(17)

In addition, the sum of the moments of forces acting on the satellite, relative to the axis of its rotation is equal to zero:
\[ F_{12} r_2 + F_{23} r'_2 = 0, \]  
(18)  

where \( r_2 \) and \( r'_2 \) are the radii of the initial circles of satellite gearing with teeth numbers \( z_2 \) and \( z'_2 \), respectively.

Conclusions

Analytical and graphical dependences for efficiency between driving and driven elements (sun gear and carrier, or vice versa) in a single-row and multi-row epicyclical gear trains with closed circuit hydrosystem obtained by means of computer simulation are shown in Fig. 3 and 5. They allow visually verifying the change of efficiency value and evaluating it in terms of self-braking.

As you can see from the graphs (Fig. 3), epicyclical gear train, where sun gear is the driving element and the carrier – driven, has efficiency higher than the one of simple transmission and significantly increases with the angular velocity of control element, while slightly decreases with increasing of gear ratio.

Graphs (Fig. 5) show that epicyclical gear train, where the driving element is carrier and sun gear is driven, has efficiency higher than the one of simple transmission, which slightly decreases with increasing of gear ratio, but increases with the raise of angular velocity of control element. Analysis of expression (16) indicates that efficiency does not reduced to zero for this quadrant and so self-braking is not possible.

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