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ANALYSIS OF EFFICIENCY OF A NEW TWO STAGE CYCLOID DRIVE CONCEPT

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Abstract: *Cycloid drives are part of a new generation of planetary gear trains. These reducers have massively appeared in the second half of the 20th century. Research on the subject of cycloid drives is an interesting subject in the field of mechanical power transmissions due to its wide use and price range which is similar to other types of conventional, planetary, and other types of reducers.*

This paper gives an analysis of efficiency of a new two stage cycloid drive concept. The efficiency analysis takes into consideration the losses due to friction in the bearing cam surface of the shaft, on the central gear rollers and the output rollers. The efficiency of the new concept of cycloid drive is given for different standard power values. In order to assess the efficiency of the new concept of the two stage cycloid drive a comparative analysis was conducted with a standard concept of two stage cycloid drive. The paper concludes with suggestions as well as possible directions for further research.

Keywords: *two stage cycloid drive, new concept, friction, losses, efficiency*

1. INTRODUCTION

One of the newest types of planetary power transmissions are definitely cyclod reducers. The cyclod reducer was invented and patented by German engineer *Lorenz Branen*,[1]. He also started production line of the cyclod reducers. Cyclod reducers are experiencing mass expansion in the second half of the 20th century. Nowadays there is a growing number of manufacturers, as well as a wider range of concepts of these mechanical power transmissions. Since then, to this day, cyclo reducers have been a very attractive subject for research in the field of mechanical gearboxes due to their wide range of applications, and because of the price ranges that resemble to other gearboxes types (conventional, planetary, etc.).

One of the most important characteristics of the gearbox is its efficiency. The first mathematical formulation of the cycloid reducer efficiency is presented in the book *Planetary Transmissions*,[2]. Based on the mathematical model presented in the book [2], *Malhotra* made a new model for determining the cycloid reducer efficiency taking into account the power losses on each cylinder of the central gear unit individually, as well as on each output roller individually [3]. *Kosse* has been investigating how is efficiency affected by the multiplication of the input torque,[4]. In the paper [5], a comparative analysis of the experimental and theoretical determination of the cycloid reducer efficiency was given, and on the basis of the obtained results, a new mathematical model was developed for determining the cycloid reducer efficiency [5,6]. *Blagojević* et al. examined the influence of friction coefficients variation on the cycloid reducer efficiency,[7]. *Neagoe* and a group of authors carried out experimental tests on the efficiency of the non-pin wheel concept of cycloid reducer,[8]. *Zah* was defined the procedure for the thermal analysis of the cyclod reducer,[9]. *Tonoli* studied the influence of the non-lubricating regime on the cycloid reducer efficiency,[10]. *Mihailidis* performed an experimental lubrication test for a cyclod reducer,[11]. *Blagojevic* et al. experimentally verified the method for determining cycloid reducer efficiency which was given by Kudrijavcev,[12].

In this paper the results of the theoretical determination of the new concept double-stage cycloid reducer is presented. That new cycloid reducer concept is given in the paper [13]. At the end of the paper, a comparative analysis between the new double-stage cycloid reducer efficiency and the existing solutions of the world's leading companies is presented.

2. EFFICIENCY OF THE NEW TWO STAGE CYCLOID DRIVE CONCEPT

The cycloid reducer efficiency analysis is a complex and attractive task, both for science and for engineering practice. This problem becomes much more complicated if multi-stage cycloid reducers are observed or, in turn, cycloid reducers have concepts that are different from commercial ones. This topic is still an insufficiently explored aspect of cycloidal power transmissions. Efficiency determination of the cycloid reducers in all theoretical models is based on the determination of power losses in the contacts of certain elements of the cycloid reducers due to the friction of sliding, or rolling. These losses occur in contact between the following elements:

- **Power loss due to friction in the bearing on the eccentric cam.** Power loss in the bearing on the eccentric cam depends on the size and type of bearing, the size of the roller bodies, the friction coefficient of the bearing, the intensity of the force on the eccentric cuff and angular velocity.

- **Power loss due to friction between the output rollers and the openings in the cycloid gear.** In the contacts between the output rollers and the opening in the cycloid gear, the rolling friction is mostly present, so the power losses are very small at this point.

- **Power loss due to friction between the teeth of the cycloid gear and the central gear.** In the contacts between the cycloid gear and the central gear, as well as in the contacts between the openings on the cycloid gear and the output rollers, the dominant is rolling friction.

- **Power loss due to friction between the output rollers and the output pins.** Output rollers are most often directly mounted on the matching axes of the output mechanism, so in this contact there are losses due to sliding friction. The variables that directly affect the power losses in this contact are: the diameter of the output pin, the sliding friction coefficient, the slip speed and the output force.

- **Power loss due to friction between the central gear rollers and its pins.** As the number of contacts of the central gear rollers and its pins large, here the greatest power losses occur due to slip friction. The greatest impact on power losses is: the pin diameter (inner diameter of the central gear roller), the sliding friction coefficient, the sliding velocity and the normal force.

The new concept of the double-stage cycloid reducer differs from the conventional concepts in that one gearbox is used for each of the transmission rates. The *CAD* model of the new concept of two stage cycloid reducer is given in Figure 1.

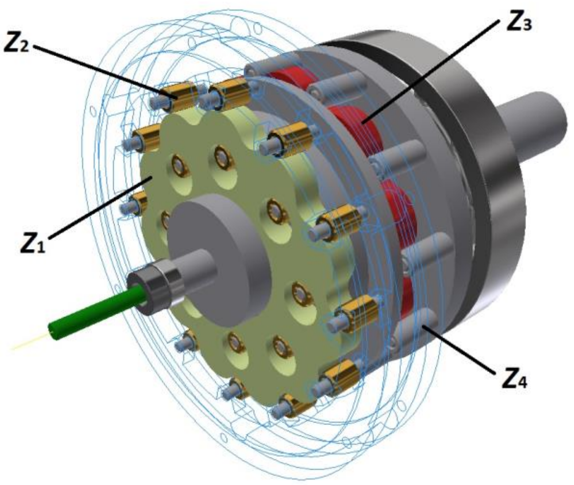


Figure 1. Double stage cycloid reducer new concept

In figure 1 are marked: z_1 – cycloid gear of first stage, z_2 – central gear of first stage, z_3 – cycloid gear of second stage and z_4 – central gear of second stage.

A modified Kudrijavcev's method was used to determine the efficiency of the double stage cycloid reducer new concept,[2]. The expression for determining the efficiency by this method is:

$$\eta=\left(\frac{1-\psi_{I}}{1+z_1\cdot\psi_{I}}\right)\cdot\left(\frac{1-\psi_{II}}{1+z_3\cdot\psi_{II}}\right), \tag{1}$$

where are: η – double stage cycloid reducer new concept efficiency, z_1 – number of teeth of first stage cycloid gear, ψ_I – power losses in first reduction stage, z_3 – number of teeth of second stage cycloid gear and ψ_{II} – power losses on second reduction stage.

Power losses of first reduction stage can be calculated by equation:

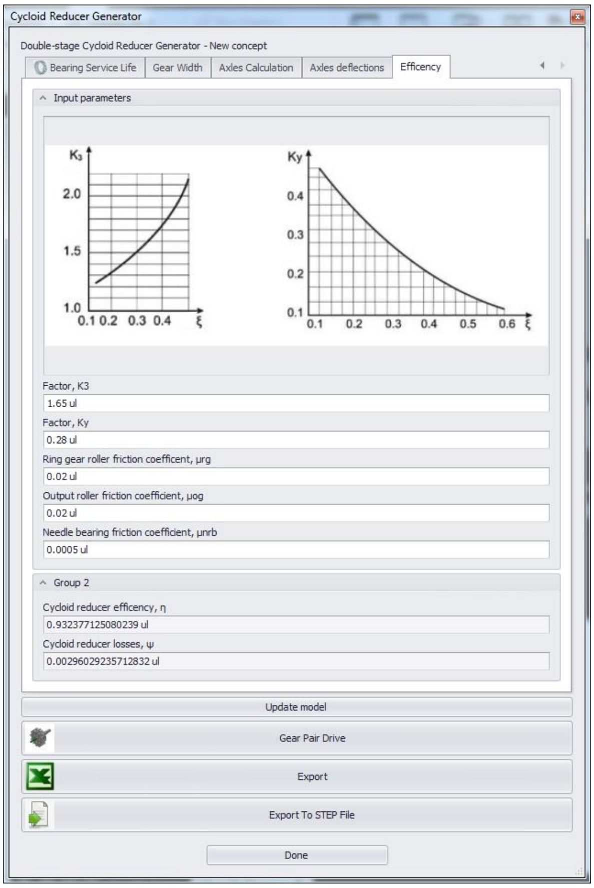
$$\psi_{I}=\psi_{I1}+\psi_{I2}+\psi_{I3}, \tag{2}$$

where are: ψ_{I1} – power loss due to friction on the central gear rollers, ψ_{I2} – power loss due to friction on the output rollers and ψ_{I3} – power loss due to friction on the eccentric cam bearing.

The power losses for the second reduction stage are calculated in the same way as for the first reduction stage (it is used same type of equation). The difference is in the value of the losses, which occurs as a result of the of different forces effect related to first reduction stage. Determination of the individual values of losses is described in detail in the literature, [12]. The described equations refer to the determination of the nominal double stage cycloid reducer new concept efficiency under previously defined working conditions.

3. EFFICENCY DETERMINATION APPLICATION

For the purposes of this research, the application was developed in the software package *Autodesk INVENTOR 2019*. The application is based on the principles presented in the second chapter of this paper as well as on the mathematical model presented in the author's previous work [12]. The user application form for determining the efficiency of double stage cycloid reducer new concept is shown in Figure 2.



Factor, K3
1.65 ul
Factor, Ky
0.28 ul
Ring gear roller friction coefficent, μrg
0.02 ul
Output roller friction coefficient, μog
0.02 ul
Needle bearing friction coefficient, μnrb
0.0005 ul
Cycloid reducer efficency, η
0.932377125080239 ul
Cycloid reducer losses, ψ
0.00296029235712832 ul

Figure 2. Application form for determining the efficiency of double stage cycloid reducer new concept

The user form for the nominal efficiency calculation of the two-stage cycloid reducer new concept is divided into two parts. The first part refers to the input of the input parameters, while the second part refers to the calculated efficiency parameters. The application is used by the user form to enter the selected values of the factors based on the diagram from the upper part of the form, which are determined according to the predefined working conditions, as well as the friction coefficients between the individual elements of the cycloid reducer. Factors K_3 and K_y are determined based on choice of the cycloid profile correction factor ξ, while the friction coefficients between the elements of the cycloid reducer are determined based on the selected material of the elements, as well as on the basis of the lubricant used in the cycloid reducer.

4. ACHIEVED RESULTS ANALYSES

Double stage cycloid reducer new concept has been analyzed for three various rotations per minute on the input shaft: n_{in}=750 min^{-1}, n_{in}=1450 min^{-1} and n_{in}=3600 min^{-1}. In the same manner, the three various transmission ratios was used, which are approximated by standard catalogue values, u=121, 165 and 231, [14-16]. Efficiency simulations for cycloid reducer are conducted for standard power values: 0,25; 0,55; 0,75; 1,5; 3; 5,5; 7,5 and 15 kW. Other parameters of cycloid reducer are adopted form literature,[2,5,6,12,13].

In figure 3 is shown efficiency for double stage cycloid reducer new concept at n_{in}=750 min^{-1} on the input shaft.

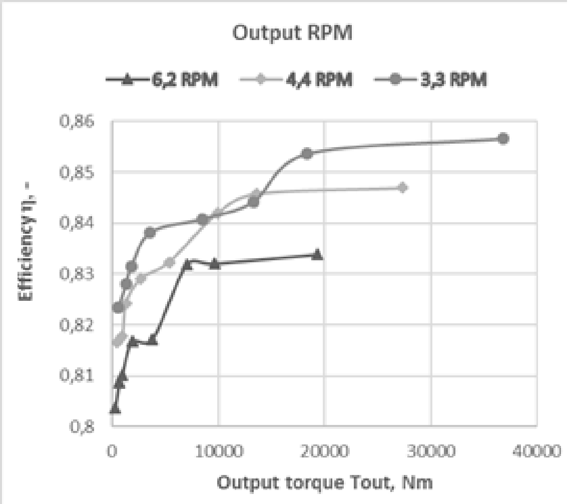


Figure 3. Efficiency diagram for 750 RPM of input shaft

The curve with triangles represents double stage cycloid reducer new concept having an approximately transmission ratio equal to the catalog of u=121; the curve with rhombuses is a gear ratio with a transmission ratio of u=165, while the curve with circles represents a gear ratio with a transmission ratio of approximately u=231. From Figure 3, it can be noticed that the gears with the lowest transmission ratio (u=121) have the lowest efficiency. The reducers with a transmission ratio of u=165 have a slightly higher efficiency while the reducers with a transmission ratio of u=231 have the highest efficiency.

In figure 4 is shown efficiency for double stage cycloid reducer new concept at n_{in}=1450 min^{-1} on the input shaft.

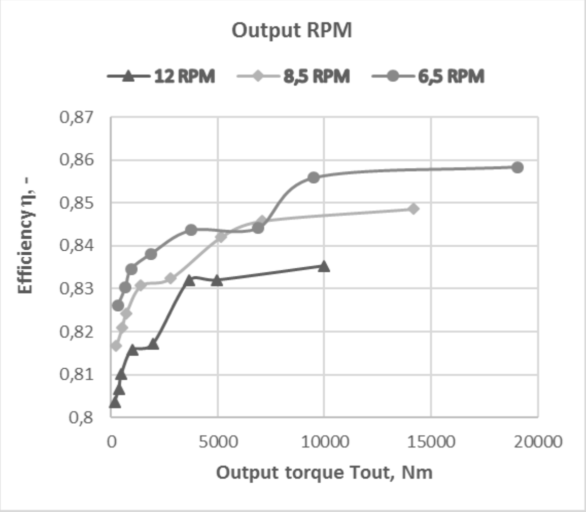


Figure 4. Efficiency diagram for 1450 RPM of input shaft

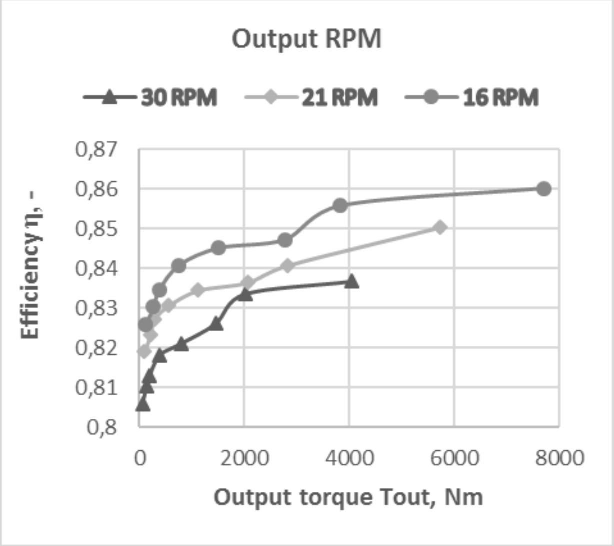


Figure 5. Efficiency diagram for 3600 RPM of input shaft

Figure 4 shows that the curves for the same transmission ratios are very similar to those of the curves shown in Figure 3. In general, the efficiency at the input shaft speed of n_{in} =1450 min^{-1} is 1 to 2% higher than the transmission ratio for the input shaft speed of n_{in} =750 min^{-1}.

In figure 5 is shown efficiency for double stage cycloid reducer new concept at n_{in}=3600 min^{-1} on the input shaft.

Figure 5 shows that the curve shapes for the same transmission ratio are very similar to the curve shapes in Figure 4. In general, the efficiency at the input shaft speed of n_{in}=3600 min^{-1} is 0.5 to 1.5% higher than transmission ratio for the input shaft speed of n_{in}=1450 min^{-1}.

5. CONCLUSION

This paper presents a methodology for efficiency determination of double stage cycloid reducer new concept. A theoretical model for determining cycloid reducer efficiency is based on the Kudrijavcev's model,[2]. In order to automate the process of determining the cycloid reducer efficiency, an application was developed in the *CAD* software *Autodesk INVENTOR 2019*.

The simulations result of determining the efficiency of double stage cycloid reducer new concept differ from the catalog results [14-17] in the interval from 2% to 5%. In according to manufacturer Nabtesco, the obtained results of cycloid reducer efficiency are from 0% to 2% greater than the catalog values. In according to Sumitomo manufacturer, the obtained results are 0% to 5% lower for double stage cycloid reducer new concept.

In the further steps of this research, it is planned to manufacture a series of new two-stage cycloidal reducers and to carry out experimental tests.

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