THEORETICAL AND EXPERIMENTAL TESTING OF PLASTIC CYCLOID REDUCER EFFICIENCY IN DRY CONDITIONS

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ABSTRACT

Cycloid drives are a relatively new group of planetary power transmissions. These transmissions have numerous favorable characteristics, such as a wide range of transmission ratios, very compact design, high reliability in dynamic exploitation conditions, high efficiency, etc. As they are part of a newer generation of transmissions, the possibility of using other materials other than steel in their production is not yet fully investigated. For the purposes of this investigation a single stage cycloid reducer was designed and manufactured out of mainly plastic components. The theoretical efficiency was determined and experimentally tested. Their comparative analysis is given through the discussion. The paper concludes with suggestions for further research on this type of cycloid reducers.

Keywords: cycloid reducer, cycloid gear, efficinency, POM, friction coefficient

AIMS AND BACKGORUND

During the past few decades cycloid drives have found a wide use in engineering practice. Cycloid power transmissions belong to the group of planetary drives. This type of planetary drive was invented and patented by German engineer Lorenz Braren in 1928[1]. Cycloid drives are most frequently used as speed reducers. Their use is widespread and they can be found in robots, satellites, manipulation devices, lifts, transporters, renewable energy devices (wind turbines, mini hydro plants...), etc. Even though they belong to the new power transmissions category, their prices are in the similar range as those of conventional power transmissions.

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Cycloid reducers have numerous benefits: wide range of transmission ratios, a compact design, a very low level of noise and vibration, high reliability under dynamic loading, a low mass, small dimensions, the possibility of transferring large amounts of torque, high efficiency, etc. Kudrijavcev created equations for achieving the profiles of cycloid gears[2]. He set forth procedures in calculating geometrical parameters for the coefficient of profile correction, and found its link to load capacity of the cycloid gear. Kudrijavcev also defined the stress distribution on cycloid reducer elements. His book 'Planetary Transmission' is the basic literature for research in this field. Lehmann in his research for his PhD thesis has added to the Kudrijavcev mathematical model of the cycloid reducer and left out a detailed analysis of forces on particular elements of a reducer[3]. The first analyses of forces in cycloid reducers considered static working regimes of cycloid reducers. These analyses largely contributed to the understanding of forces behavior in cycloid reducers, while a much larger practical application was given in dynamic behaviour analyses of cycloid reducers[4–6]. Yang and Blanche considered tolerances in cycloid gear production and tested the influence of tolerances on cycloid reducer operation[7]. Malhotra created a model for determining the efficiency of cycloid reducers[8]. The other mathematical model for determining efficiency was created by Gorla et al.[9] Very interesting research comparing these two models was conducted by Mačkić and a group of authors[10–11]. Efficiency research was completed by Blagojević including the influence of wear and behavior of cycloid reducers in exploitation[12–13]. Important contribution to researching efficiency was given by Sensinger[14]. He used optimization as a tool for achieving parameter values which would increase cycloid reducer efficiency. Recently, papers with research of improved cycloid gear profile dynamic testing have been published[15]. An important aspect of research on cycloid reducers researched the phenomena of heat, and heat distribution[16].

One of the rare papers on the topic of plastic cycloid gearing was written by Biernacki[17]. This research is indirectly related to cycloid reducers, but it is related to cycloid gearing for gerotor pumps. This research was the inspiration and motivation for the research work presented in this paper. Beirnacki used POM plastic for manufacturing a gerotor pump impeller. He concluded that it is possible to use this type of plastic in gerotor pumps with particular profile corrections.

This paper presents a comparative analysis of theoretical and experimental research of a plastic cycloid reducer efficiency.

DESIGN AND MANUFACTURING OF PLASTIC CYCLOID REDUCER

While desiging the reducer it was desided that the following parts will be made out of plastic materials: housing (PA6), covers (PA6), output rollers (POM) and central gear rollers (POM) as well as the cycloid gear (POM). Other elements are

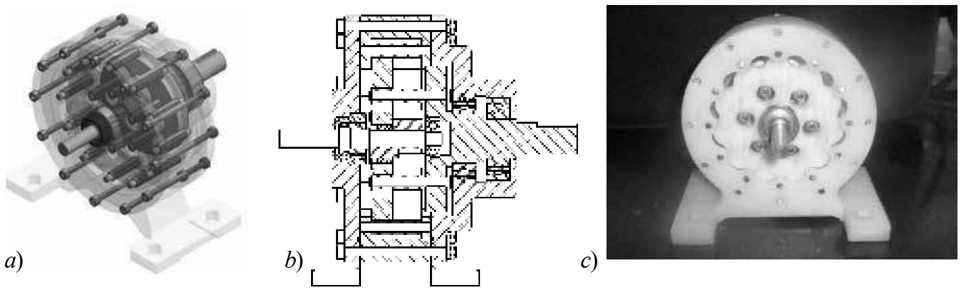


Fig. 1. Tested cycloid reducer: *a*) 3D model; *b*) cross-section; *c*) manufactured reducer

made out of steel C45 (Č1530). This step leads to a drastical change in overall mass of the cycloid reducer, better vibration absorption during operation, etc. This model enables the testing of sliding friction in the plastic roller (POM) and steel pin (C45) in assembly under real working conditions. For the purpose of speeding up the design process of the cycloid reducer an algorithm for automatic generation of specific elements, and testing of the functionality of the drives kinematic structure was used[18]. The design and construction of the cycloid reducer are shown in Fig. 1.

The cycloid gear, due to its precise and complex manufacturing, was created in the Center for testing and calculation of machine elements and systems at the home faculty. The Cycloid gear was made on a Roland Modela MDX-40a milling machine. The assembling of the cycloid reducer was also done in the Center. Prior to the assembly a visual and measurement inspection was conducted of all parts. Upon assembling the system's functionality was assessed in order to prepare the reducer for testing.

THEORETICAL ANALYSIS OF EFFICIENCY

The theoretical analysis of efficiency was conducted in two ways: for nominal efficiency, and for momentary efficiency according to momentary working conditions. According to Kudrijavcev[2], nominal efficiency depends only on geometric parameters of the cycloid reducer and on the friction coefficient. Nominal efficiency is calculated according to the equation:

$$\eta_{CR} = \frac{1-\psi}{1+z_1 \cdot \psi} \tag{1}$$

where are: η_{CR} - nominal efficiency; ψ – the coefficient of total losses due to friction within the cycloid reducer; and z_1 – number of cycloid gear teeth. The coefficient of total losses due to friction within the cycloid reducer is calculated according to the equation:

$$\psi = \psi_1 + \psi_2 + \psi_3 \tag{2}$$

where the notations are: ψ_1 – coefficient of losses due to friction in the central gear rollers; ψ_2 – coefficient of losses due to friction on the output rollers; and ψ_3 – coefficient of losses due to friction in the needle roller bearing. The calculation of these coefficients is described in detail in the literature[2].

Analysis of momentary efficiency is in its essence done in a similar manner to the analysis of normal efficiency (1), with losses ψ_2 and ψ_3 being determined differently. In this case loss coefficients depend on angular speed and torque. The coefficient of losses from friction in the output rollers in this case is calculated using the following equation:

$$\psi_2 = \frac{P_{Nv}}{T_3 \cdot \omega_3} \tag{3}$$

where the notations are: P_{Nv} – power loss due to friction on the output rollers, W; T_3 – torque on the cycloid gear, Nm; and ω_3 – angular speed of the cycloid gear, s^{-1}. Power which is lost on the output rollers is calculated using the following equation:

$$P_{Nv} = \frac{4 \cdot T_3}{\pi \cdot R_0} \cdot e \cdot \omega_3 \cdot f_{pv} \tag{4}$$

where the notations are: R_0 – radius of the cycloid gear holes' placement, mm; e – size of the cam eccentricity, mm; and f_{pv} – friction coefficient factor between the output roller and pin.

Coefficient of losses due to friction in the needle roller bearing ψ_3, is determined according to the following equation:

$$\psi_3 = 1.25 \frac{T_T}{T_3} \tag{5}$$

where T_T is friction torque, Nm. Friction torque is calculated according to the following equation:

$$T_T = 1.3 \cdot k \cdot \left(1 + \frac{D_{ec}}{d_{kt}}\right) \cdot F_\mu \tag{6}$$

where the notations are: k – rolling friction coefficient in the needle bearing[2], k=0.005, mm; D_{ec} – cam diameter, inner diameter of the needle bearing, mm; d_{kt} – diameter of the needle in bearing, mm; and F_μ – friction force, N.

Friction force intensity is calculated according to the following equation:

$$F_\mu = \frac{T_3}{r_2}\sqrt{1+\left(\frac{4}{\pi}\cdot\frac{r_2}{R_0}-K_y\right)^2} \tag{7}$$

where the quantities are: r_2 – radius of the movable circle, mm; R_0 – radius of the cycloid gear holes' placement, mm; and K_y – factor dependent on the correction factor of the cycloid reducer[2].

EXPERIMENTAL SETUP

Experimental testing is conducted on the test rig GUNT AT 200, which was adapted for the purposes of this research work. The experiment was conducted in the Center for testing mechanical transmissions, at the home faculty. The experiment is conducted in two ways: measuring input and output forces using analogue dynamometers, and then using force sensors. Using analogue measuring the experiment is conducted by measuring the input torque at a set number of revolutions per minute. The input torque is measured so that the electric motor is placed on a rotational bracket with a lever on the free end, which is tied to the analogue dynamometer. According to the dynamometer readings and multiplying them with the length of the lever the input torque is calculated. The output torque is measured by the force on the electromagnetic break lever. The output torque is determined by multiplying the force readout with the length of the break's lever. The analogue force measurement is presented in Fig. 2.

The experiment with force sensors is done similarly to the experiment with analogue measuring devices. The only difference being that a sensor bracket, and

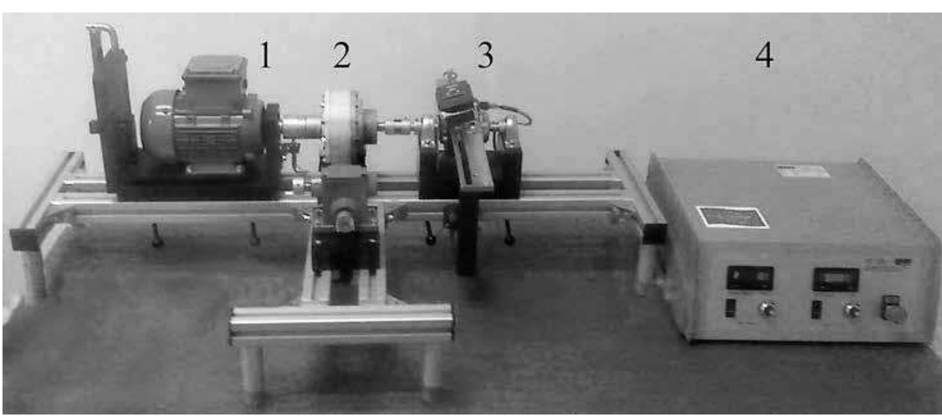


Fig. 2. Analogue force measuring: *1* – electric motor with torque measuring; *2* – plastic cycloidal reducer; *3* – magnetic brake with torque measuring; *4* – frequent regulator

a) *b*) *c*)

Fig. 3. Measuring force using force sensors: *a*) input force sensor; *b*) output force sensor; *c*) signal amplifier and system for data acquisition

signal amplifier with data acquisition system are added to the measuring procedure. Additions to the experiment are shown in Fig. 3.

The angular speed and torque are attained via a frequency regulator. Experiments are conducted without lubrication, or additional cooling. This approach is chosen as the plastic has self-lubricating capabilities.

RESULTS DISCUSSION

In order to analyze the calculated efficiency of the plastic cycloid reducer, input geometry characteristics of the developed reducers are necessary. Aside from geometrical characteristics of the reducer elements, the dimensions of the needle bearing, as well as the friction coefficients in the contact of C45 and POM are needed. Required data are given in Table 1.

Table 1. Data for efficiency calculation

Name	Symbol	Value	Units
Number of cycloid gear teeth	z_1	11	–
Number of central gear rollers	z_2	12	–
Diameter of central gear roller pin	d_{nv}	4.5	mm
Diameter of central gear roller	D_{nv}	7.2	mm
Cam eccentricity	e	2.5	mm
Cycloid gear profile correction factor	ξ	0.35	–
Radius of movable circle	r_2	30	mm
Radius of the cycloid gear holes' placement	R_0	21.95	mm
Diameter of output roller pin	d_{pv}	4.5	mm
Diameter of output roller	D_{pv}	7.1	mm
Outer cam diameter	D_{ec}	15	mm
Diameter of needle bearing roller	d_{kt}	2	mm
Friction coefficient in rollers (C45-POM)[19]	$f_C=f_{pv}'$	0.21	–
Factor (Fig. 3)	K_3	1.6	–
Factor (Fig. 3)	K_y	0.25	–

According to given data and methods for calculating efficiency an algorithm for calculation was developed in MS Excel. Determination of efficiency is done for the case of nominal efficiency as well as momentary efficiency.

In order to determine the momentary efficiency under certain regimes, according to the set torque and set angular speed, it was necessary to calculate friction coefficients for the various regimes. This calculation was done according to the literature[9], using squared polynomials, which includes input torque and coefficients *a*, *b*, and *c*. According to the experiments the input torque is set according to breaking force until the system achieves balance, and measurements are done between 100 to 850 min^{-1} with a division of 50 min^{-1} (Fig. 4).

Results of the momentary efficiency, as well as results of experimental measurements are shown on the diagram in Fig. 5.

Each iteration in measuring is done according to the previously explained experiment plan. In the first iteration of measurement a large divergence from the calculated values of friction coefficient appears. The analogue measurement results diverge more. This can be attributed to inprecise readings of the analogue dynamometer during data aquisition. The second measurement shows significant-

Fig. 4. Values of angular speeds and torque during the experiments

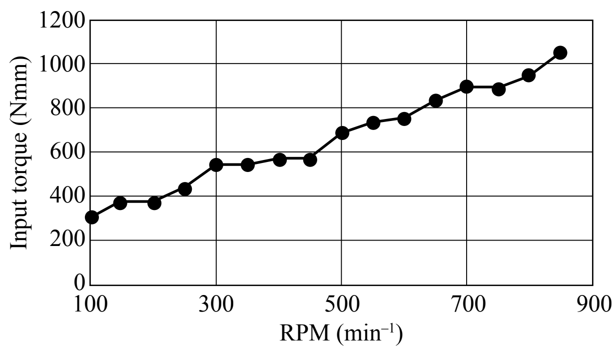
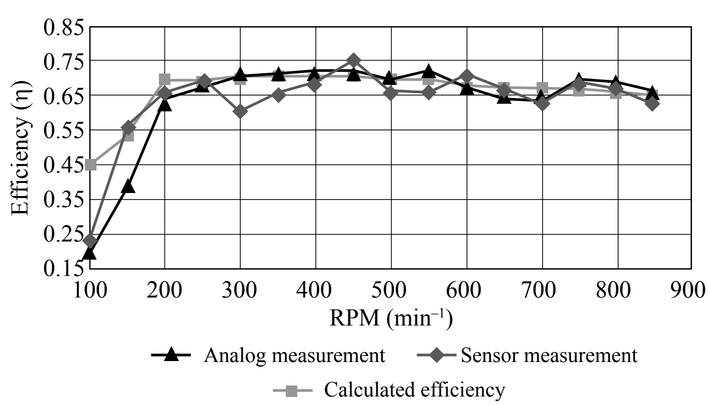


Fig. 5. Results of calculated and experimental efficiency



ly closer results to calculated values. From the third to the last, sixteenth measurement, divergence of results are in acceptable ranges[9]. Friction coefficients in all measurements are within limits from the literature[19]. The first two measurements give friction coefficients in the upper limits, while all other measurements show them near the lower limit. From the given diagram (Figure 5) it can be seen that efficiency increases up to 300 revolutions per minute. Above this the efficiency has a set value which largely resembles that of the calculated nominal efficiency.

CONCLUSION

Through this research work, it was concluded that the cycloid reducers with mostly plastic parts can have a very high efficiency in dry working conditions. The only disadvantage found was that its dynamic stability is only possible with small input angular speeds. This could be overcome if lubrication, ventilation or cooling would be introduced. Future research could be orientated on researching rolling friction and its implementation into the calculation model for efficiency.

Development of a new model of efficiency, as well as research work in the field of plastic cycloid reducers is possible in regimes under lubrication, ventilation, or cooling.

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