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Preliminary communication

Efficiency Calculation of Cycloid Reducer with Plastic Meshing Elements

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Abstract: Cycloid power transmissions belong to the group that can be classified as planetary gear trains. These power transmissions, reducers, are part of the latest generation of power transmissions, related to the conventional ones. Cycloid power transmissions have a wide range of applications in industries such as transporters, robots, satellites, etc. This research presents an analysis of various analytical methods that can be used in determining cycloid drive efficiency. The paper explores the most well-known mathematically formulated procedures and compares them to the experimental results conducted in the testing of cycloid reducer which is made mainly of plastic parts meshing parts and housing is made of plastic. The procedures presented for assessing efficiency share a common characteristic: they all calculate losses attributed to friction between the bearing and the eccentric shaft, the friction on rollers of the ring gear, and the friction on output rollers. The presented research points to the most suitable method for efficiency calculation. The experimental testing is conducted for one standard-sized reducer which is designed and manufactured specially for this research. The main product of the paper is giving clear guidelines for plastic cycloid reducer efficiency calculation. The paper shows that plastic used in the tested reducer can be used instead of metals in sensitive reducer applications.

Keywords: calculation method; cycloid reducer; efficiency; plastic cycloid disc

1 INTRODUCTION

In the recent times, cycloid reducers found very wide usage in engineering practice. Cycloid reducers are predominantly utilized as cycloid reducers. These reducers exhibit several favorable characteristics, including a compact design, minimal vibration and noise during operation, reliable performance under dynamic stress, low mass relative to the transmitted power, a broad range of achievable transmission ratios, and the capacity to deliver high torque output. Cycloid reducers find applications in various fields such as robotics, manipulators, transporters, and processing technology machinery. The cost of cycloid reducers falls within a similar range as conventional drives, despite belonging to a newer generation of power transmissions. A crucial attribute of cycloid reducers is their high efficiency. This paper will outline the determination of efficiency through diverse methods and include a comparative analysis of these approaches. The notable attribute of cycloid reducers, their elevated efficiency, will be addressed in the paper through the calculation of efficiency using different methods, accompanied by a comparative analysis of the said methods.

The cycloid reducer efficiency is a quite important aspect in designing these types of reducers. The first literature source, with complete forces and efficiency analysis, was shown in the book Planetary Gear Train [1]. This book has an entire chapter related to cycloid reducers, which presents the basis for many investigations, including nowadays research. Based on the efficiency equations of the cycloid reducer in the mentioned book, Malhotra made a new model for the cycloid reducer efficiency calculation [2]. His model for efficiency calculation considers the power losses on each ring gear roller individually, and also on every output roller individually. Some researchers tested how cycloid drive efficiency influences multiple input torque increases [3], based on the first two mentioned models. Gorla et al. did an analysis that compares the efficiency determined through experimentation with the theoretically calculated efficiency for the cycloid reducer drive which was manufactured and tested in their research facility [4]. They subsequently used the results in order to create a new set of equations for the efficiency calculation of cycloid reducers [4, 5]. The mentioned efficiency model is used for efficiency calculation of new cycloid reducer concept. Blagojevic et al. performed the testing of influence during the changing friction coefficients between cycloid reducer elements [6], which is based on Kudrivajvcev's force analysis. The procedure for cycloid reducers thermal analysis has been defined by the group of researchers [7], and the thermal analysis relation of the efficiency was defined. Tonoli et al. investigated the impact of dry operation on cycloid reducers efficiency [8], which is based on their previous research [4]. Mihailidis has conducted an experiment which proved Malhotra's method for cycloid reducer efficiency calculation [9]. A group of authors experimentally verified one of the methods for cycloid reducer efficiency determination [10, 11]. In some new research papers, it can be noted that efficiency calculation is expanded to the new cycloid reducer concepts [12-14]. The latest research in the cycloid reducer efficiency field is oriented on the tolerance and cycloid disc profile modifications impact on the efficiency as well [15-18]. Some of those researches are orientated in designing high-efficiency cycloid drives of new concepts [19]. The interesting aspect of the cycloid reducers efficiency research is using different types of lubricants (oils) as well [20]. One of the interesting things in this field are investigations about comparing the two different efficiency calculation methods [21]. In recent times, some researchers reopened topics about profile modification and its influence on cycloid reducer accuracy. Wang et al. have performed very detailed research on this topic both theoretical and experimental [22]. A very similar research was performed by Li et al. [23] but for different reducer types. The very interesting research supported by Spinea company was performed to test the positioning accuracy of their reducers [24]. In that research 48 hours continuous run of the reducer under loading conditions was performed. Liu et al. did positioning accuracy research on the cycloid reducer [25]. All of those new research papers are dealing with increasing of cycloid reducer accuracy due to their sensitive applications in robots. In the newer research articles [26, 27] there is shown appliance of these reducers in hard conditions. All of those papers investigate the efficiency of steel reducers, as steel is the most common material in reducers production. The aspect of new materials usage is necessary to be investigated as well in cycloid reducer manufacturing as in cycloid reducers efficacy. This is a need because of possible sensitive applications and in terms of reducer recycling after its lifetime is served.

After a deep literature review, it can be noticed that three different methods of efficiency calculation are used most often [1, 2, 4]. These presented methods have verification in the available literature. Most of the reviewed papers represent a single approach or use a single method for cycloid drive efficiency calculation, whether it is an experimental or theoretical investigation. The reviewed papers also show only one working condition state. As well there are not so many research papers that introduce the ability to use a new material, such as plastics or composites, in the manufacturing of cycloid reducers. This paper represents the determination of cycloid reducer efficiency by using of the most known and proven methods. All of the used methods will be discussed in detail, and their good and bad properties will be pointed out, which is novel because so far only two methods compared in one research can be found. After detailed analysis one of those methods will be picked for comparing the experimental results. The experiment was done with cycloid drive mostly manufactured from plastic parts, which introduce a new type of material into the cycloid drives field. During the experiment, the functionality and efficiency of that cycloid drive will be shown, which shows justification for introducing new materials. So, this paper has two goals: first to compare the most widely accepted efficiency calculation methods, and second to use the most suitable one to determine the efficiency of the plastic cycloid reducer. The efficiency determination of the plastic cycloid reducer is done both by calculation and by experiment for the various working regimes. The paper, at the end, gives good and bad aspects of introducing new materials, as well as with efficiency determination comparison (theoretical vs. experimental).

2 CYCLOID REDUCER EFFICIENCY CALCULATION METHODS

Cycloid reducer efficiency analysis is a highly intricate and challenging research problem. This problem is very interesting in engineering practice and scientific endeavours as well, especially due to cycloid reducer expansion in robotic and electric vehicle applications. Their efficiency is still a topic that lacks thorough exploration or investigation, especially in the aspect of new materials usage in their production. Detailed model representations for cycloid reducer efficiency calculation are extensively covered in various research papers [1, 2, 4]. Those models can be called respectively: Kudrijavcev model, Malhotra model, and Gorla model. Efficiency calculation for each of mentioned theoretical models relies on assessing power losses on specific locations between meshing and moving cycloid reducer elements. These losses occur due to rolling and sliding friction. The elements where these power losses occur include:

- Power losses occur because of the friction in the cycloid disc bearing which is located on the eccentric shaft. This loss is influenced by factors such as bearing size and type, force intensity on the eccentric shaft, the angular velocity, the size of the rolling element and bearing rolling friction coefficient.

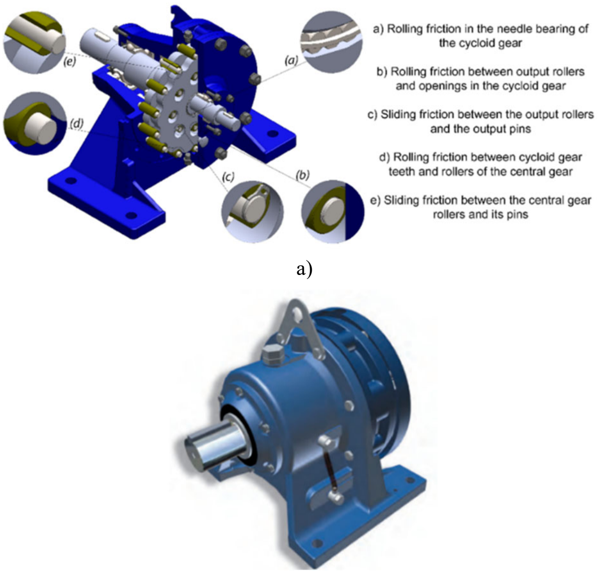
- Power losses occur as well from the rolling friction between output rollers and holes in the cycloid disc. In these contacts the rolling friction is dominant. This spot leads to minimal and almost negligible power losses. The Gorla model does not take into account these power losses because the number of output rollers is relatively small compared to the rollers of the ring gear [4].

- Power losses that occur because of the rolling friction between the cycloid disc teeth and the ring gear rollers. In the mentioned contacts, rolling friction is the biggest influence, giving very small power losses. The magnitude of these losses depends on the friction coefficient between rolling elements and the normal forces which act there.

- Power losses from sliding friction in the contact between output pins and output rollers. Because the output rollers are in almost every cycloid reducer concept directly mounted on the corresponding output pins, there are losses attributed to sliding friction. These contacts act as a sliding bearing. The factors directly influencing power losses in the mentioned contact include the sliding speed, the output force, the outer pin diameter (inner diameter of the output roller), the sliding friction coefficient, pin and hole tolerances, etc.

- Power losses from sliding friction in the contact of rollers and the ring gear pins. In most cycloid reducer designs, the ring gear rollers are directly assembled onto the corresponding pins. As this contact is numerous, it experiences the most significant power losses attributable to sliding friction. The primary factors influencing power loss in this contact are sliding friction coefficient, normal forces, the diameter of the pins (inner roller diameter), pin and hole tolerances, etc.

A better insight of the power losses placement is shown in Fig. 1a, while assembled cycloid reducer unit is shown in Fig. 1b.



a)

b)

Figure 1 Cycloid reducer: a) power losses placement [28]; assembled cycloid reducer unit from catalogue, [29] In Kudrijavcev's model [1], the power loss determination in interacting elements takes into account the following losses: power losses in the eccentric shaft bearing, power losses in the ring gear rollers and their pins, and power losses in the output rollers and their pins. In accordance with this method, other power losses are considered as negligible. The complete power loss in accordance with Kudrijavcev's model is calculated by the following equation:

$$\psi = \frac{K_3 \cdot \mu_3}{z_3} + \frac{4 \cdot e \cdot \mu_{VK}}{\pi \cdot R_0} + 1{,}63 \cdot \left(1 + \frac{d_{cz}}{d_{kt}}\right) \cdot \frac{k}{r_2} \cdot \sqrt{1 + \left(\frac{4}{\pi} \cdot \frac{r_2}{R_0} - K_y\right)} \tag{1}$$

where: K_3 - is the cycloid disc correction factor coefficient, μ_3 - ring gear and their pins friction coefficient, z_2 - ring gear rollers number, e - eccentricity, μ_{VK} - output rollers and their pins friction coefficient, R_0 - cycloid disc holes placement radius, d_{cz} - eccentric shaft diameter, d_{kt} - cycloid disc rolling bearing element size, k - friction force arm of the cycloid disc bearing, $k = 0{,}005$, r_2 - moving circle radius and K_y - cycloid disc tooth correction factor.

The factor values K_3 and K_y, and their choice, are explained in detail in papers [10-12].

In accordance with Kudrijavcev's model, cycloid reducer efficiency is calculated by the following equation:

$$\eta = \frac{1 - \psi}{1 + z_1 \cdot \psi} \tag{2}$$

where: z_1 - is the number of teeth in cycloid disc, ψ - is power loss coefficient.

Malhotra's model for the efficiency calculation [2] is based on the calculation of the friction forces total work which occurs during a cycloid disc elementary angular movement by dθ, [2]. In cycloid disc rotation by dθ, then the input shaft will rotate by an angle of $i \cdot \mathrm{d}\theta$, while the ring gear rollers will rotate by an angle of $(i + 1) \cdot \mathrm{d}\theta$. In that statement, i represents the transmission ratio of the cycloid reducer, or cycloid disc teeth number. All the power losses in the interaction between cycloid reducer elements can be calculated by the equation:

$$\begin{aligned} W = \int_0^{\frac{2\pi}{i}} dW = \frac{\mu_{r1} D_m i}{d_{kt}} \int_0^{\frac{2\pi}{i}} F_E(\theta)\mathrm{d}\theta + i\left(\mu_{r2} + \frac{\mu_{s1} d_{VK}}{2}\right) \int_0^{\frac{2\pi}{i}} \sum_{j=1}^{q} F_{Kj}(\theta)\mathrm{d}\theta + \\ +(i+1)\left(\mu_{r3} + \frac{\mu_{s2} d_0}{2}\right) \int_0^{\frac{2\pi}{i}} \sum_{i=1}^{p} F_{Ni}(\theta)\mathrm{d}\theta \end{aligned} \tag{3}$$

where are: μ_{r1} - rolling bearing friction coefficient, $F_E(\theta)$ - eccentric force current value, D_m - cycloid disc bearing diameter, d_{kt} - cycloid disc rolling bearing element size, μ_{r2}- rolling friction coefficient in contact point of cycloid disc and output roller assembly, $F_{Kj}(\theta)$ - j-th output roller current force, q - current contact number of output shaft rollers and cycloid disc holes, μ_{r3} - rolling friction coefficient in point of contact between cycloid disc and ring gear roller assembly, $F_{Ni}(\theta)$ - i-th roller of the ring gear normal force current value, p - rollers number of the ring gear which are in contact at the given moment the ones which are transmitting load, μ_{s1} - coefficient of sliding friction in contact point of input rollers and output pins, d_{VK} - output pins diameter, μ_{s2} - sliding friction coefficient in contact with ring gear rollers and pins and d_0-ring gear pin diameter.

In accordance with Malhotra's cycloid reducer efficiency model the following equation is used:

$$\eta = \frac{T_{u1} \cdot 2\pi - W}{T_{u1} \cdot 2\pi} \tag{4}$$

where are: η - cycloid reducer efficiency and T_{u1} - is the input reducer torque.

In accordance to Gorla [4], cycloid reducers efficiency calculation is based on calculation of the following power losses:

- Rolling friction between the input eccentric shaft and cycloid disc power loses.

- Sliding friction between output rollers and holes in the cycloid disc (as the rolling friction is changed for sliding friction due to this concept not having output rollers, but just output pinsin this contact, there is an obvious difference from the previous shown model) power loses.

- Power loses because of the friction in the contact of the cycloid disc, ring gear rollers and ring gear (in this contact there is sliding friction on the contact of the cycloid disc with the rollers of the ring gear, while on the part of the contact between the ring gear rollers and the ring gear there is rolling friction).

The complete power loss in accordance with Gorla's model can be calculated using the following equation:

$$W = T_{u1} \cdot (\omega_i - \omega_0) + \sum_{i=1}^{n} F_{Ti} \cdot v_{Ki} + \sum_{j=1}^{m} \mu_{Kj} \cdot F_{Kj} \cdot v_{Kj} \tag{5}$$

where: ω_i - inner bearing ring on the eccentric shaft angular speed, ω_0 - outer bearing ring on the eccentric shaft angular speed, T_{u1} - input reducer torque, F_{Ti} - contact force between the shaft and hole, v_{Ki} - referent coordinate system sliding speed, μ_{Kj} - friction coefficient in contact between output shaft and hole and F_{Kj} -j-th output roller current force.

Lastly, the equation for cycloid reducer efficiency in accordance to Gorla method is:

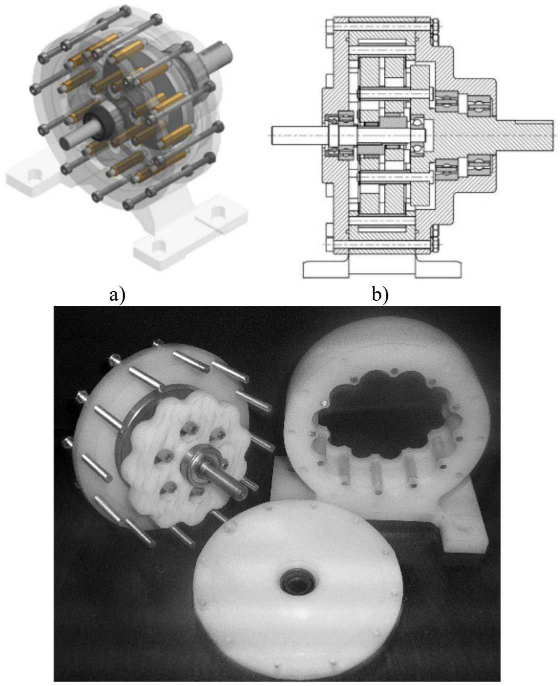
$$\eta = \frac{P_{u1} - W}{P_{u1}} \tag{6}$$

where: P_{u1} - input shaft power.

The three cycloid reducer efficiency determination models are presented here. Detailed explanations for the usage of all three models are referenced. Kudrijavcev's model, as the oldest one, is mostly experimentally verified and its results fit with lead world cycloid reducer manufacturers data. Malhotra's model is very detailed, but it is proven only for small cycloid reducer sizes, which is a big constraint in model usage. Gorla's model is detailed but it is limited, with proofs, to only one reducer type which is described in paper [4]. As Kudrijavcev's model is the most accepted one, and experimentally proven in various literature sources, it is chosen as the most reliable one in further discussion.

3 EXPERIMENTAL SETUP

For the purpose of this research, the cycloid reducer mostly of plastic materials has been made. During reducer design phase it was decided that the following parts will be made from plastic materials: housing (PA6), covers (PA6), output rollers (POM), and ring gear rollers (POM) as well as the cycloid disc (POM). Other elements are made out of steel (C45). The material selection was based on the author's practice experience. This step leads to a drastic change in the overall mass of the cycloid reducer, better vibration absorption during operation, corrosion resistance, etc. This cycloid reducer model enables the testing of sliding friction in the contact of steel pin (C45) and plastic roller (POM) in assembly under real working conditions. In Fig. 2 is shown 3D model of cycloid reducer, section view of cycloid reducer and manufactured unit used for experimental testing.

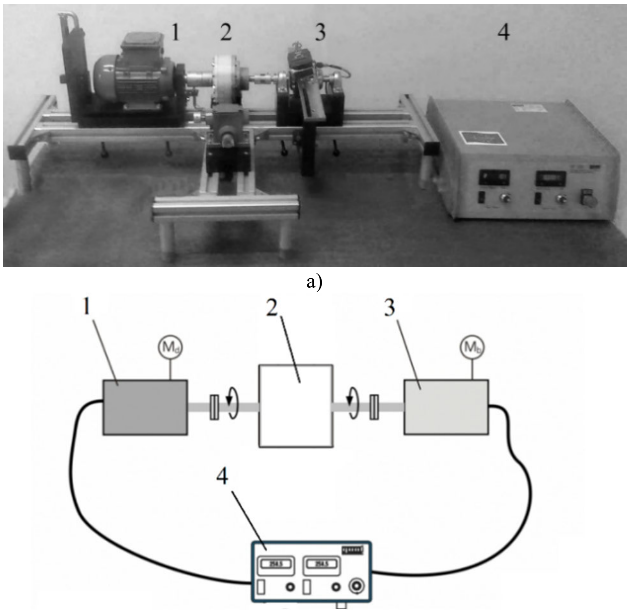

a) b)

c)

Figure 2 Tested cycloid reducer: a) 3D model; b) cross-section c) manufactured reducer

The cycloid disc, due to its precise and complex manufacturing, was manufactured in the Center for testing and calculation of machine elements and systems at the home institution. The cycloid disc was made on a milling machine Roland Modela MDX-40a. The assembling of the cycloid reducer unit was performed in the Center as well. Prior to assembly, a visual and measurement inspection was conducted on all parts. Upon assembling the system's functionality was assessed in order to prepare the reducer for testing.

Experimental testing is conducted on the test rig GUNT AT 200, located in the Center for power transmissions testing at the Faculty of Engineering, University of Kragujevac, which was modified for the presented research purposes. The experiment was conducted in the Center for testing mechanical transmissions, at the home institution. The input torque was measured so the electric motor is placed on a rotational bracket with a lever on the free end which is tied to the force sensor. According to the force sensor readings and multiplying them with the length of the lever the input torque was calculated. The output torque is measured by the force on the electromagnetic brake lever. The output torque is determined by multiplying the force readout with the length of the brakes lever. Fig. 3 shows the experimental setup and its schematics view.

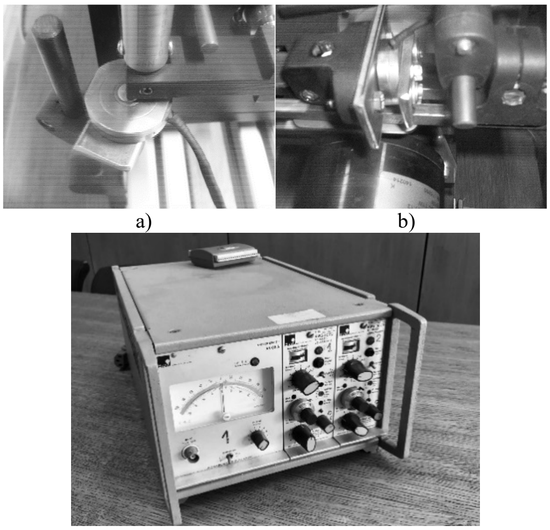


a)

b)

Figure 3 Base variant of force measuring: 1) electric motor with torque measuring; 2) plastic cycloid reducer; 3) magnetic brake with torque measuring; 4) frequent regulator: a) real testing rig; b) testing rig schematics

Testing rig improvements were done. Two force sensors with brackets were added. The force sensors which were used there are from lead sensor manufacturer HBM. The force sensor designation is HBM C9C. The sensors have accuracy class of 0.2 and they are for examination for a wide range of temperature conditions from –10 to +70 °C, which fits real work conditions. Sensors were patched to the signal amplifier. A signal amplifier was connected to the data acquisition device. Additions to the test rig GUNT AT 200 are shown in Fig. 4.


a) b)

c)

Figure 4 Measuring force using force sensors: a) input force sensor; b) output force sensor; c) signal amplifier and system for data acquisition

The rotational speed and torque are varied via a frequency regulator. Experiment testing was conducted without lubrication or additional cooling. This approach is chosen because of the following reasons:

- The plastic has self-lubricating capabilities.
- The application of lubricant and its possible leakage in sensitive reducer application could have very bad consequences.
- In industrial application of plastic materials there is possibility that the plastic, due to the lubricant usage, can gain a bit of expansion which can have a negative influence on the reducer performance characteristics.
- Some lubricants can have negative influence to the meshing surfaces of the plastic reducer parts etc.

4 RESULTS DISCUSSION

In the represented research as the most representative model the Kudrijavcev's method has been chosen for the cycloid reducer efficiency calculation. In the context of this study, a cycloid reducer with the characteristics given in Tab. 1 was produced and experimentally tested.

Table 1 Cycloid reducer characteristics selected for the purposes of this research

Name of value	Nomenclature	Value	Unit
Motor power	P	0.34	kW
Nominal RPM	n	1400	RPM
Center axis height	H	75	mm
Ring gear radius	r	45	mm

From Tab. 1 data, a CAD model of the single-stage cycloid reducer was produced. Utilizing a CAD model, essential geometric values for efficiency calculation, following Kudrijavcev's method, were derived. The efficiency calculations were conducted across speeds ranging from 100 RPM to 850 RPM, with an incremental distribution of 50 RPM. The nominal electric motor input power is 0.34 kW. The selection of this reducer and angular speeds was based on the maximum power and rotational speed of the test rig.

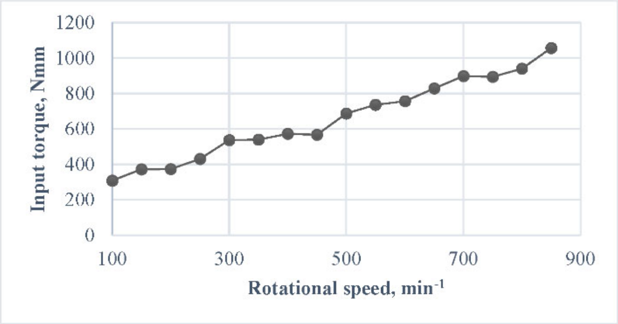


Figure 5 Input shaft torque diagram

The diagram of used rotational speeds and torque is shown in Fig. 5, as well as the diagram of input power related to RPM in Fig. 6. As is shown in Fig. 3, for the control of the rotational speed is used a frequent regulator; electric motor transmits the much smaller power to the system on the smaller rotational speed. As rotational speed increases at some point frequent regulator gives the nominal power to electric motor. The point of nominal electric motor power is at 1400 RPM. After that point the power starts to decrease. The reason for the usage of small motor power is a test rig size limitation. For testing of bigger reducers the custom test rig is required. The reason why the 850 RPM is used as upper RPM limit is that above that limit the manufactured unit starts to heat and does not have a stable work.

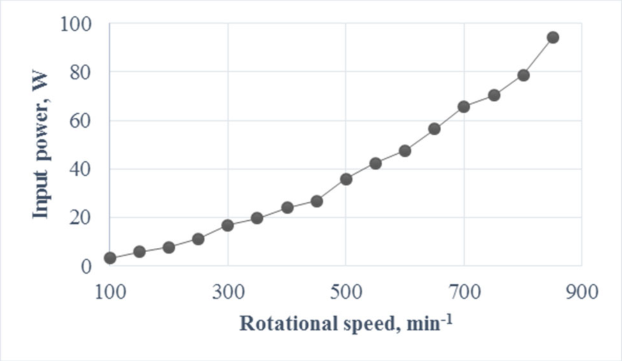


Figure 6 Input power from electric motor

Using this approach it is feasible to directly compare the calculated theoretical results with the experimental results. The analytical calculation and experimental results deviation, related to the input torque, are shown in Fig. 7.

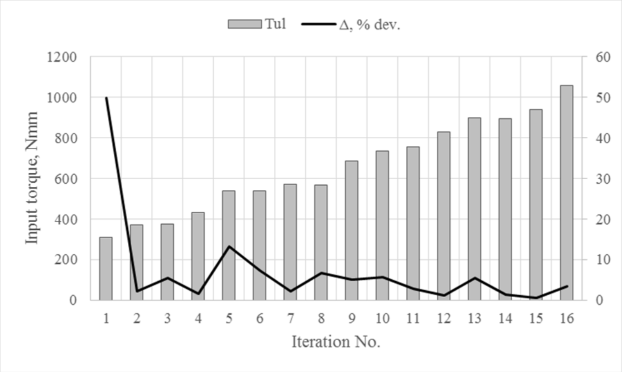


Figure 7 The analytical calculation and experimental results deviation, related to the input torque

In order to have a better insight into the experimental results the comparative efficiency diagram has been made and shown in Fig. 8. Excluding iteration 1 from consideration, the theoretical calculations and experimental measurements for determining efficiency fall within the range of 0.61% to 13.25%.

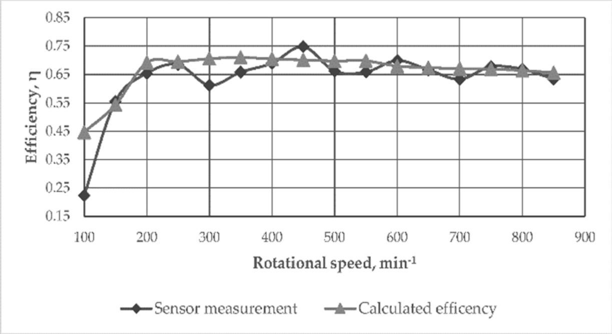


Figure 8 Theoretical cycloid reducer efficiency determining according to Kudrijavcev vs experimental results

Upon closer examination of the Malhotra and Kudrijavcev efficiency calculation methods, it becomes evident that both models are designed for cycloid reducer concepts incorporating ring gear rollers. Notably, these models share numerous similarities in the determination of power losses. The authors posit that a comparison between theoretical and experimental efficiency determinations would likely reveal no significant differences from the outcomes of the Kudrijavcev model. However, the preference for Kudrijavcev's model is justified by its proven applicability across various types and sizes of cycloid reducers, whereas Malhotra's model is limited to the classic cycloid reducer with small input power.

Gorla's model is grounded in the evaluation of efficiency for a casually different cycloid reducer concept. In this particular design, the cycloid reducer does not have traditional rollers; rather, it directly connects through pins positioned between the ring gear and the cycloid disc. The research by Gorla et al. highlights that the disparity in efficiency determination between theoretical calculations and experimental measurements using his method falls within the range from 0% to 8.5%[4].

Kudrijavcev's and Gorla's procedures for calculating efficiency represent two fundamentally distinct mathematical models. Despite the differences in their mathematical approaches, these models share similarities in identifying losses at corresponding locations. The disparities between the methods extend beyond mathematical aspects, encompassing conceptual differences arising from the utilization of distinct designs for cycloid drives. In terms of deviations from theoretical calculation to experimental measurement results, Gorla's method displays variations within the range from 0% to 8.5%, whereas Kudrijavcev's model ranges from 0.61% to 13.25%. In the deviation of the results in the Kudrijavcev's model was not considered 1st iteration of the experiment, because of very small input rotational speed. The Gorla model displays slightly smaller deviations, and Malhotra's model, based on the same cycloid reducer concept as Kudrijavcev's model, shares considerable mathematical similarities. Consequently, the authors posit that conducting a comparison of theoretical results and experimental findings for Malhotra's model would likely yield deviations no larger than those observed in the procedure of Kudrijavcev, particularly for input powers (up to 0.12 kW). The Kudrijavcev's calculation holds a minor edge over the Malhotra's calculation because it is somewhat easier for use in efficency calculations of cycloid reducer. The advantage of Kudrijavcev's model lies in that it is proven on the various sizes, concepts and input powers for cycloid reducers.

5 CONCLUSIONS

The paper represents the known mathematical procedures for efficiency calculation of a single stage cycloid reducer, [1, 2, 4]. The presented investigation discusses the contemporary research on the cycloid reducers efficiency. Following this, a comprehensive overview of the methodologies proposed by Kudrijavcev, Gorla and Malhotra, is provided. This paper shows the comparative analysis, comparing the efficiency calculations with the experimental results for a predominantly plastic-based cycloid reducer. The conducted experiments yield multiple sets of values.

- The operating of the mostly plastic cycloid reducer is proven, which leads to a larger usage of those materials in a cycloid reducer field. The usage of plastics in cycloid reducers can have the following good effects: drastic change in the overall cycloid reducer mass, better vibration absorption during working conditions, corrosion resistance, etc.
- The plastic reducer operating experiment was conducted without a lubricant because the chosen plastic materials had self-lubrication properties.
- For the RPM's input bigger than 100 RPM, the Kudrijavcev's method shows reliability for the new plastic reducer, even in dry conditions. The used method has a pretty similar deviation of theoretical vs. experimental related to the Gorla's method.
- The deviation between experimental and theoretical results in the RPM's input of 100 and less can be described as common occurrence in all reducer types. Namely on such a small RPM's input every reducer efficiency goes below 50% and straight to 0%.
- The authors reached 850 RPM at 0.1 kW power with stable working of the manufactured reducer. On higher RPM the reducer started to heat, because experimental testing was done without lubrication.
- This experiment was done to prove the use of mostly plastic made cycloid reducer in sensitive industrial applications; authors do not recommend using the same experimental setup for examination of metal made reducers.

The authors' forthcoming research endeavors in this domain are anticipated to encompass the experimental validation of Malhotra's method, particularly focusing on larger input power sizes. Additionally, future investigations are expected to involve the formulation of a general mathematical model for cycloid reducers efficiency calculation, irrespective of the concept. This will be complemented by experimental validation of the newly devised model.

A great contribution of the work also consists in the fact that a database of test results was formed. The test results can be statistically processed using one of the available methods [30, 31], which enables further optimization of the Cycloid Reducer, saving time and resources.

Nomenclature

D_m - cycloid disc bearing diameter,
d_0 - ring gear pin diameter,
d_{cz} - eccentric shaft diameter,
d_{kt} - cycloid disc rolling bearing element size,
d_{VK} - output pins diameter,
e - eccentricity,
$F_E(\theta)$ - eccentric force current value,
$F_{Kj}(\theta)$ - j-th output roller current force,
F_{Ti} - contact force between the shaft and hole
$F_{Ni}(\theta)$ - i-th roller of the ring gearnormal force current value,
K_3 - parameter that takes into account the tooth correction of the cycloid disc,
K_y - factor that incorporates the cycloid disc tooth correction,
k - friction force arm of the cycloid disc bearing, $k = 0,005$,
P_{ul} - input shaft power (EM power),
P - number of rollers of the ring gear which at the given moment are in the process of transmitting load,

R_0 - cycloid disc holes placement radius,

r_2 - moving circle radius,

T_{ul} - input reducer torque,

q - current contact number of output shaft rollers and cycloid disc holes,

z_2 - ring gear rollers number,

v_{Ki} - referent coordinate system sliding speed

η - cycloid reducer efficiency,

μ_3 - ring gear and their pins friction coefficient,

μ_{Kj} - friction coefficient in contact between output shaft and hole,

μ_{r1} - rolling bearing friction coefficient,

μ_{r2} - rolling friction coefficient in contact of output rollers and cycloid disc,

μ_{r3} - rolling friction coefficient in contact of cycloid disc and ring gear rollers,

μ_{s1} - sliding friction coefficient in contact of input rollers and output pins,

μ_{s2} - sliding friction coefficient in contact of ring gear rollers and pins,

μ_{VK} - output rollers and their pins friction coefficient,

ω_i - inner bearing ring on the eccentric shaft angular speed and

ω_o - outer bearing ring on the eccentric shaft angular speed.

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