Vol. 42, No. 2 (2020) 337-343, DOI: 10.24874/ti.880.05.20.06

Tribology in Industry

www.tribology.rs

RESEARCH

Efficiency Analysis of New Two-Stage Cycloid Drive Concept

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Keywords:

Two stage cycloid drive
New concept
Friction
Losses
Efficiency

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Received: 5 March 2020
Revised: 7 May 2020
Accepted: 5 June 2020

A B S T R A C T

A new generation of planetary speed reducers has a lot of various reducer concepts. One of the new type are cycloid drives. A massive appearance of cycloid drive reducers is related to the second half of the 20th century. This type of reducers represent a very interesting and attractive mechanical power transmission research field. The main reason for research interest is that cycloid reducers has a large potential in practice usage and they have very similar price related to conventional, planetary and other reducer types.

Efficiency analysis of new two-stage cycloid drive concept is presented in this paper. The efficiency is determined based on losses due to friction in the bearing eccentric shaft surface, on the central gear rollers and the output rollers. New two-stage cycloid drive concept efficiency is done for 8 standard power values from 0.25kW to 15kW, with various input RPM and various transmission ratios. In order to evaluate the efficiency of new two-stage cycloid drive concept, the comparison with existing solutions in practice has been made. At the end of the paper are given conclusions with possible directions of research continuation.

1. INTRODUCTION

Cycloid speed reducers are one of the most recent planetary power transmission type. This type of power transmission was invented and patented by L. K. Braren [1], who was German engineer employed at company Fredrick Deckel. L. K. Braren started his own production line of this type of reducers. Massive expansion of cycloid reducers happened in the second half of the 20th century. Today, there is a couple of world leading cycloid reducer manufacturers, but that number started to grow with Asian market expansion. There are, as well, a much wider range of concepts of cycloid speed reducers. Since they stepped to the market, to nowadays, these reducers have been a very interesting topic for research in the field of mechanical power transmission due to their large possibilities in applications at various industries. The cycloid reducers are as well interesting due to price ranges that are very competitive to other speed reducer types such as conventional, planetary, etc.

Efficiency is certainly on of the most important property of all types of speed reducers. First mathematical model of cycloid reducer efficiency was established and presented in the book Planetary Transmissions, [2]. Malhotra [3] used a mathematical model presented in the book [2] to establish his own model of cycloid reducer efficiency. Malhotra made a few improvements on his model: he took into account power losses on every tooth (cylinder) on the central gear individually and on each output roller individually as well. Kosse has conducted investigation of the efficiency by taking into account how efficiency is acting by the multiplication of the input torque, [4]. In the paper [5] is presented the comparison between experimental and analytical efficiency. Based on that results the new mathematical model has been established and presented, [5,6]. Blagojević et al. conducted an investigation of the influence of friction coefficient variation on the efficiency of cycloid reducer, [7]. Neagoe with group of authors did a experimental testing on the non-pin wheel cycloid reducer concept efficiency, [8]. Zah made a definition of the procedure for the thermal calculation of the cycloid gearbox, [9]. Tonoli exanimated the impact of the non-lubricating regime on the cycloid reducer efficiency, [10]. Mihailidis conducted an experimental lubrication test for a cycloid reducer in various setups, [11]. Blagojevic et al. did experimental validation of the method for cycloid reducer efficiency determination which was presented by Kudrijavcev, [12].

This paper presents a theoretical establishment of the new concept of two-stage cycloid reducer efficiency. The new two-stage cycloid reducer concept is presented and explained in details in paper, [13]. The paper concludes with comparative analysis between new two-stage cycloid reducer efficiency and existing solutions of the world's market as well as new directions of research described.

2. EFFICIENCY OF THE NEW TWO-STAGE CYCLOID DRIVE CONCEPT

Analyses of cycloid reducer efficiency is very complex and demanding task in engineering practice and as well as science task. The efficiency analysis is becoming much more complicated task if the multi-stage reducers are considered because this type of reducers are very different related to the conventional ones.

The investigation field of cycloid reducer efficiency analysis is not yet very well investigated. Cycloid reducer's efficiency is, in all theoretical models, based on power losses in contact on its elements due to the friction of sliding, or rolling, or even both. The power losses occurs in the contact between following cycloid reducer 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 two-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 Fig. 1.

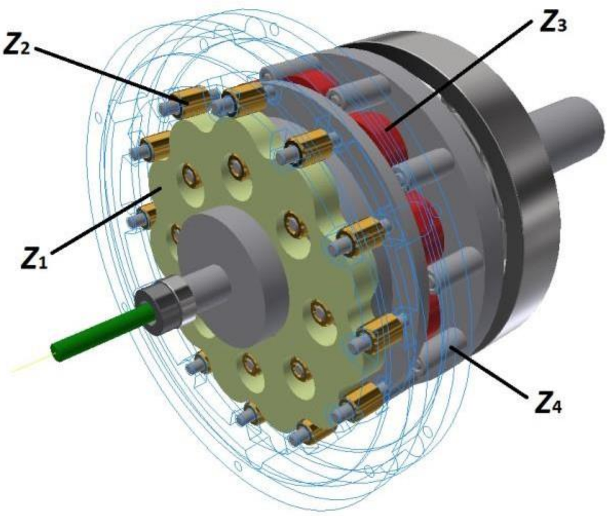

Fig. 1. Two-stage cycloid reducer new concept.

In Fig. 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 two-stage cycloid reducer new concept, [2]. The expression for determining the efficiency by this method is:

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

where are: η – two-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:

$$\psi_{\mathrm{I}} = \psi_{\mathrm{I1}} + \psi_{\mathrm{I2}} + \psi_{\mathrm{I3}}, \quad (2)$$

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 different forces effect related to first reduction stage. Calculation of the individual values of losses is described in detail in the literature, [12]. The described equations refer to the determination of the nominal two-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 calculating the efficiency of two-stage cycloid reducer new concept is shown in Fig. 2.

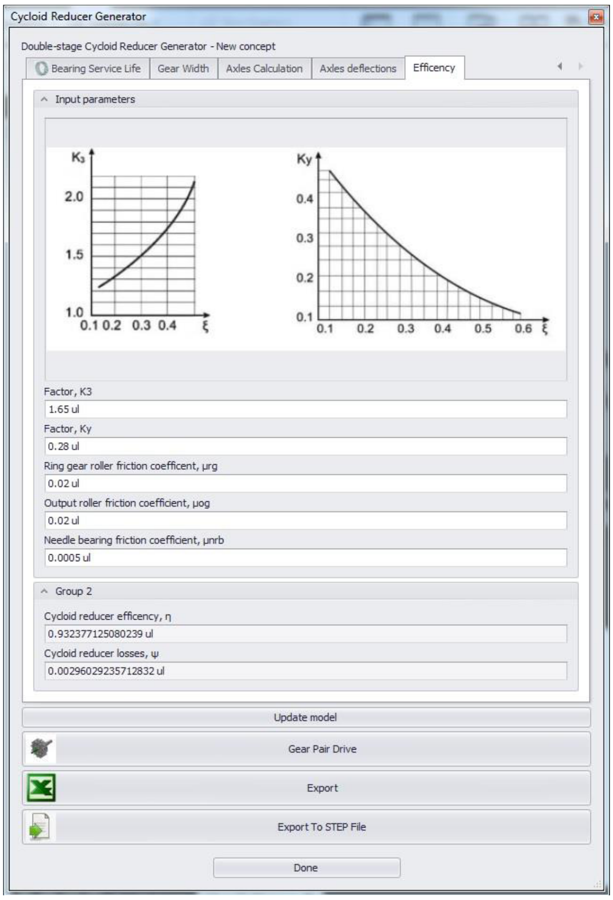

Fig. 2. Application form for determining the efficiency of two-stage cycloid reducer new concept

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

Two-stage cycloid reducer new concept has been analyzed for seven various rotations per minute on the input shaft which are shown in Table 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].

Table 1. Transmission ratios and input/output RPM for selected gearboxes.

n_{in}	u=121	u=165	u=231
750	6.2	4.5	3.2
800	6.6	4.8	3.5
915	7.6	5.5	4.0
1140	9.4	6.9	4.9
1450	12.0	8.8	6.3
2850	23.6	17.3	12.3
3600	29.8	21.8	15.6

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

The curve with triangles represents two-stage cycloid reducer new concept having an approximately transmission ratio equal to the catalogue 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.

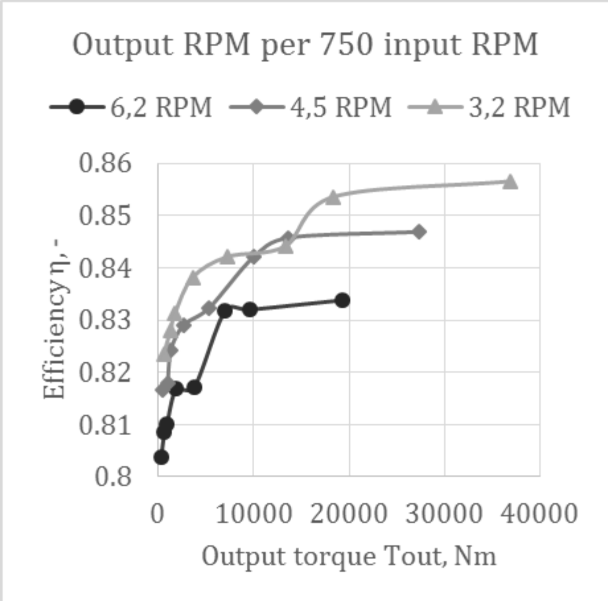

Fig. 3. Efficiency diagram for 750 RPM of input shaft.

In Fig. 4 is shown efficiency for two-stage cycloid reducer new concept at n_{in}=800 [min^{-1}] on the input shaft.

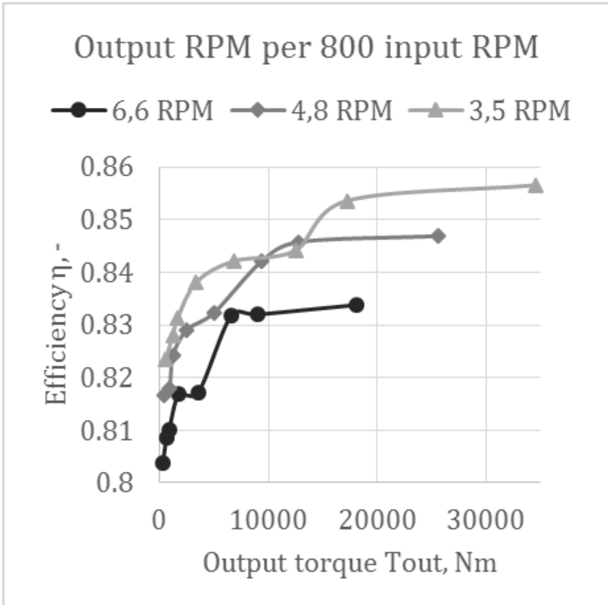

Fig. 4. Efficiency diagram for 800 RPM of input shaft.

In Fig. 5 is shown efficiency for-stage cycloid reducer new concept at n_{in}=915 [min^{-1}] on the input shaft.

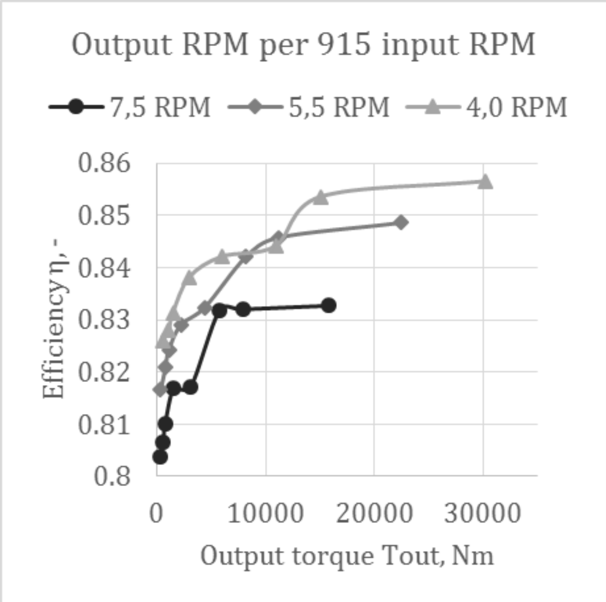

Fig. 5. Efficiency diagram for 915 RPM of input shaft.

In Fig. 6 is shown efficiency for two-stage cycloid reducer new concept at n_{in}=1140 [min^{-1}] on the input shaft.

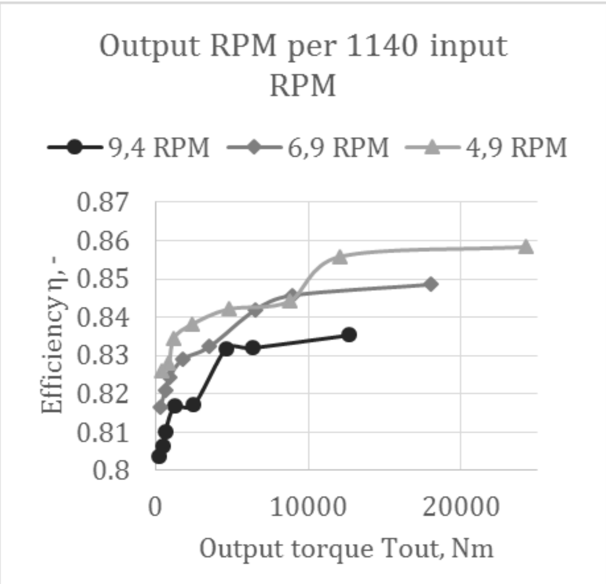

Fig. 6. Efficiency diagram for 1140 RPM of input shaft.

In Fig. 7 is shown efficiency for two-stage cycloid reducer new concept at n_{in}=1450 [min^{-1}] on the input shaft.

In Fig. 8 is shown efficiency for two-stage cycloid reducer new concept at n_{in}=2850 [min^{-1}] on the input shaft.

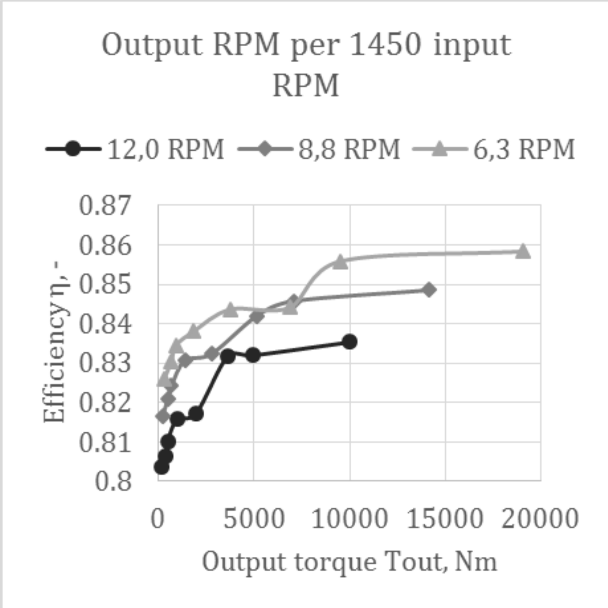

Fig. 7. Efficiency diagram for 1450 RPM of input shaft.

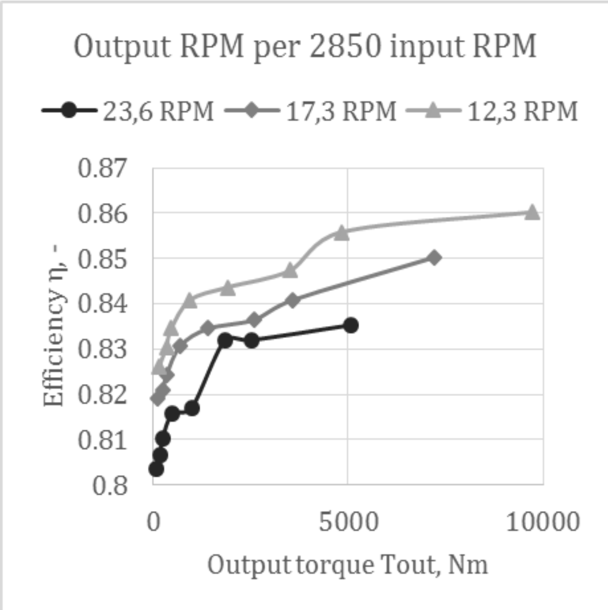

Fig. 8. Efficiency diagram for 2850 RPM of input shaft.

In Fig. 9 is shown efficiency for two-stage cycloid reducer new concept at n_{in}=3600 [min^{-1}] on the input shaft.

Figures 3 to 9 shows that the curves for the same transmission ratios are very similar to each other. 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}]. Transition in efficiency improvement can be noticed on small amounts from figure 3 to 7. In Fig. 9 is shown efficiency for two-stage cycloid reducer new concept at n_{in} = 3600 [min^{-1}] on the input shaft.

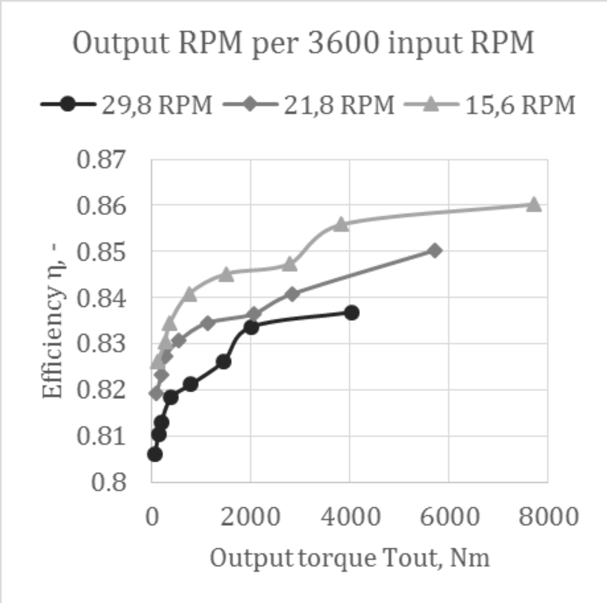

Fig. 9. Efficiency diagram for 3600 RPM of input shaft.

Figure 9 shows that the curve shapes for the same transmission ratio are very similar to the curve shapes in Fig. 7. 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}]. The Fig. 8 shows transition in efficiency between n_{in} = 1450 [min^{-1}] and n_{in} = 3600 [min^{-1}].

5. CONCLUSION

This paper presents a methodology for efficiency determination of two-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 two-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 two-stage cycloid reducer new concept.

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

Acknowledgement

This paper is a result of TR33015 and TR32036 project of the Ministry of education, science and technological development, in Serbia. The projects are titled "Research and development of a Serbian zero-net energy house", and "Development of software for solving the coupled multi-physical problems" respectively. We would like to thank the Ministry of education, science and technological development on their financial support during this research.

REFERENCES

[1] L.K. Brarren, *Gear transmission*, U.S. Patent 1,694,031, 1928.

[2] V.N. Kudrijavcev, *Reducers with cycloidal gearing.* Planetary Transmissions, Moscow, pp. 251-271, 1966. (in Russian)

[3] S.K. Malhotra, M.A. Parameswaran, *Analysis of a cycloid speed reducer*, Mechanism and Machine Theory, vol. 18, iss. 6, pp. 491-499, 1983, doi:10.1016/0094-114X(83)90066-6

[4] V. Kosse, *Using hysteresis loop and torsional shock loading to assess damping and efficiency of cyclodrives*, in 4th International Congress on Sound and Vibration, 9-12 July 2007, ICSV14, Cairns, Australia, pp. 1-8.

[5] P. Davoli, C. Gorla, F. Rosa, C. Longoni, F. Chiozzi, A. Samarani *Theoretical and experimental analysis of a cycloidal speed reducer*, in 10th ASME International power transmission and gearing conference, 4- 7 September, 2007, Las Vegas, USA, doi:10.1115/DETC2007-34098

[6] C. Gorla, P. Davoli, F. Rosa, F. Chiozzi, A. Samarani, *Theoretical and experimental analysis of a cycloidal speed reducer*, Journal of Mechanical Design, vol. 130, iss. 11, p. 8, 2008, doi:10.1115/1.2978342

[7] M. Blagojevic, M. Kocic, N. Marjanovic, B. Stojanovic, Z. Djordjevic, L. Ivanovic, V. Marjanovic, *Influence of the friction on the cycloidal speed reducer efficiency*, Journal of the Balkan Tribological Association, vol. 18, vo. 2, pp. 217-227, 2012.

[8] M. Neagoe, D. Diaconescu, C. Jaliu, L. Pascale, R. Saulescu, S. Sisca, *On a new cycloidal planetary gear used to fit mechatronic systems of res*, in 11th International Conference Optimization of Electrical and Electronic Equipment, 22-24 May 2008, OPTIM 2008, Brasov, Romania, pp. 439-

448, doi:10.1109/OPTIM.2008.4602446

[9] M. Zah, D. Lates, V. Csibi, *Thermal calculation for planetary cycloidal gears with bolts*, Acta Universitatis Sapientiae - Electrical & Mechanical Engineering, vol. 4, pp. 103-110, 2012.

[10] A. Tonoli, N. Amati, F. Impinna, J. G. Detoni, S. Ruzimov, E. Gasparin, K. Abdivakhidov, *Influence of dry friction on the irreversibility of cycloidal speed reducer*, in World Tribology Congress, 8-13 September 2013, Turin, Italy, vol. 5, pp. 1-4.

[11] A. Mihailidis, E. Athanasopoulos, E. Okkas, *Efficiency of a cycloid reducer*, in International Gear Conference, 26-28 August 2014, Lyon, France, vol. 2, pp. 794-803.

[12] M. Blagojevic, M. Matejic, N. Kostic, N. Petrovic, N. Marjanovic, B. Stojanovic, *Theoretical and experimental testing of plastic cycloid reducer efficiency in dry conditions*, Journal of the Balkan Tribological Association, vol. 23, no. 2, pp. 367-375, 2017.

[13] M. Blagojevic, N. Marjanovic, Z. Djordjevic, B. Stojanovic, A. Disic, *A new design of a two-stage cycloidal speed reducer*, Journal of Mechanical Design, vol. 133, iss. 8, p. 7, 2011, doi: 10.1115/1.4004540

[14] Sumitomo Drive Technologies, *Cyclo Drive 6000 Gearmotors & Speed Reducers*, catalogue, 2019.

[15] Sumitomo Drive Technologies, *Fine Cyclo Zero Backslash Precision Gearboxes*, catalogue, 2018.

[16] Nabtesco, *Precision Reduction Gear RV/ E Series/C Series/Original Series/*, catalogue 2019.

[17] Nabtesco, *Precision Reduction Gear RV/ N Series/*, catalogue 2019.