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THE USE OF THE CYCLOIDALDRIVE BLOCK IN THE ANALYSIS OF THE CYCLOIDAL REDUCER EFFICIENCY

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Abstract: Cycloidal reducers are well-known for their compact construction and high gear ratio which makes them essential in many industrial applications. The analysis of their efficiency involves precise simulations, which can be effectively done using modern software. In this paper, a cycloidal reducer model was developed using the MATLAB software in the Simulink environment. The use of the new CycloidalDrive block enables a detailed analysis and simulation of its performance. This paper will show how to obtain results using this model and to what extent these results are consistent with the expected values.

Key words: Cycloidal drive, Efficiency, MATLAB

1 INTRODUCTION

Cycloidal reducers are widely recognized for their compact construction and high gear ratio, but what really sets them apart is their high efficiency that enables efficient power transmission in various industrial systems. Modern research employs software tools for detailed modelling and analysis of these power transmissions, which provides possibilities for their further improvement.

A lot of researchers have analysed cycloidal reducers focusing on their different aspects, including efficiency. *Kudryavtsev* [1] developed methodology for estimation of power losses based on simplified models for calculation of forces and thus significantly contributed to a better understanding of their functionality. *Malhotra* [2] improved the *Kudryavtsev* model for evaluation of the cycloidal reducer efficiency, focusing on a more precise determination of the contact forces. *Vasić* [3] included both the *Malhotra* and the

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Kudryavtsev model in his study and showed that they gave similar results, with difference of up to 6,34%. He also concluded that the *Malhotra* model provided more accurate results because it took a wider range of factors into account. *Olejarczyk* [4] experimentally investigated efficiency using different types of liquid lubricants (mineral and synthetic oils) at different loads and speeds. *Mačkić* [5] analysed the influence of design parameters on the efficiency of cycloidal reducers and determined that the optimal choice of these characteristics could significantly improve the efficiency of the cycloidal reducer. *Olejarczyk* [6] compared the efficiency of cycloidal reducers with different types of cycloidal disc eccentric bearings (sleeve and needle bearings). The obtained experimental results show that, regardless of the bearing type, at the same loads and speeds, the efficiency values are similar, with a difference of up to 2%. *Mihailidis* [7] analysed efficiency using a thermo-elastohydrodynamic lubrication (TEHL) model, where friction in the contact area is determined based on complex tribological processes. *Blagojević* [8] analysed efficiency of cycloidal reducers taking into account the friction in the contact points between the cycloidal disc and the central rollers using two analytical models.

As for the use of software tools, *Guixiang* [9] analysed modifications of the cycloidal gear tooth profile using MATLAB simulation in order to improve precision of transmission and stability of operation. *Upadhyay* [10] used MATLAB and Adams software for simulation and analysis of the contact forces between cycloidal discs and the corresponding rollers. *Zhao* [11] analysed contact forces in RV reducers. *Blagojević* [12] applied MATLAB-Simulink to solve displacement equations for a two-stage cycloidal reducer of a new design, paving the way for analysis of the influence of various parameters on dynamic behaviour of the system. Using the MATLAB GUI interface for parametric design of the gear profile, *Qiao* [13] developed a platform which allows users to change parameters and monitor results in real time. *Sai* [14] analysed the cycloidal gear using a CMM machine. The errors were processed and analysed in MATLAB using the least-squares approach.

Based on the review of the prior research, it can be concluded that a lot of researches have studied the efficiency of a cycloidal reducer from different perspectives, and that the main component, the cycloidal disc, has been most often analysed in MATLAB. This paper presents a new model to analyse the cycloidal reducer efficiency. The analysis was carried out in MATLAB, in the Simulink environment, using the new *CycloidalDrive* block that simulated the operation of cycloidal reducers. The goal was to check the validity of this approach and determine how the obtained results differ from the results obtained using mathematical models.

2 DEVELOPMENT OF SIMULATION MODEL

In this paper, a model of a cycloidal reducer was created and simulated in the Simulink environment. The goal was to determine how reliably the model can predict efficiency under different operating conditions. A special attention was paid to the proper arrangement and connection of the blocks within the model in order to ensure precise and stable operation of the system. Different blocks from the Simulink and Simscape packages were used to create this model. They enabled a detailed analysis of the key components of the cycloidal reducer.

2.1 Key components of the model

The *CycloidalDrive* block from the Simscape package was used to simulate the cycloidal reducer in the Simulink environment. Figure 1a shows the external view of the block with three ports: B, R, and F. The port B (Base) is the inlet port connected to the input shaft, the port R (Ring Gear) enables the rotation of the ring gear, while the port F (Follower) is connected to the output shaft. The rotational motion of the ring gear through the port R is included in the simulation, which enables a more detailed analysis of the dynamic behaviour of the system. The simulation also includes interactions between the cycloidal disc and the ring gear, taking into consideration the forces and the moments generated in their contacts. The ports enable connection of the block to the rest of the model and thus the simulation of the power transmission. Figure 1b shows the inside of the *CycloidalDrive* block, where the key parameters for the simulation are defined. These parameters include the number of the cycloidal disc teeth and the number of the ring gear rollers. In addition, the system efficiency parameters are adjusted, as well as the power threshold below which the efficiency simulation is not performed. The *CycloidalDrive* block creates a detailed simulation of the cycloidal reducer operation. It provides possibility to adjust the input parameters such as torques and system inertia and thus enables an accurate assessment of the cycloidal reducer efficiency.

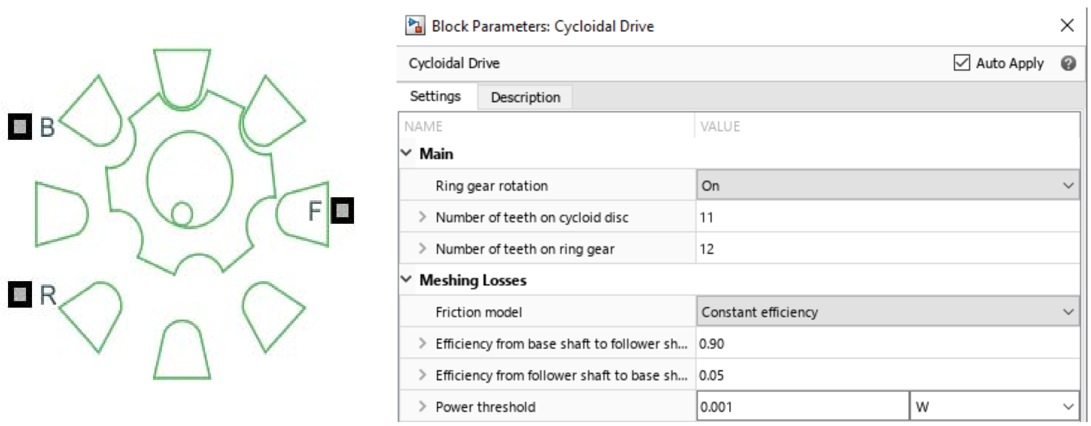

Figure 1. *a) The external view of the block; b) The internal view of the block*

In addition to the *CycloidalDrive*, another vital component for this efficiency analysis is the block that enables monitoring of the power in the system. Figure 2 shows the Power Sensor block which measures the torque and the rotation speed at the input and output shafts of the cycloidal reducer. The collected data are crucial for calculation of the efficiency of the power transmission. These parameters enable monitoring of the performance and identification of losses. The ports R, C and S are mechanical inputs, while P is the physical signal of the output power.

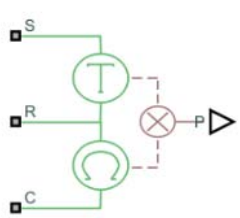

Figure 2. *Power Sensor block*

Data on dynamic characteristics together with other parameters such as torques, number of teeth and moments of inertia form the basis for the efficiency analysis.

2.2 Simulink model

As part of this research, a model of a cycloidal reducer was developed using the Simulink environment in MATLAB. The model consists of several blocks, but the crucial block is the *CycloidalDrive* which simulates the operation of the cycloidal reducer. PS Constant blocks are used to set constant torque values. The blocks Torque 1 and Torque 2 define the torques on the input shaft and the ring gear. On the other hand, the PS Constant block Torque 3 generates the torque value at the output shaft of the cycloidal reducer. These blocks enable stable power transmission through the system, which is essential for the analysis of efficiency and dynamic behaviour of the cycloidal reducer. It should be pointed out that the torque value at the ring gear refers only to one cycloidal disc. As the model uses two cycloidal discs, the torque at the ring gear should be adjusted accordingly. This enables a more accurate load analysis and ensures more realistic simulation results. Figure 3 shows the complete Simulink model of the cycloidal reducer with connected components for input and output signals.

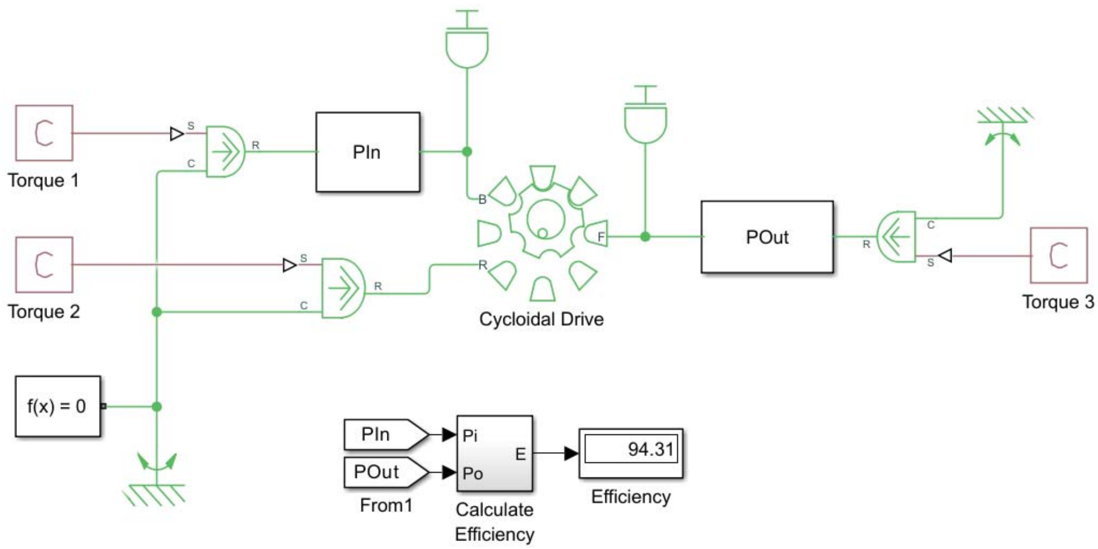

Figure 3. *The layout of the complete model*

With efficiency of 94.31%, the simulation results show that the system is highly efficient and that there are minimal losses in power transmission. The power was measured at the input and output shafts, and the results obtained are in line with expectations for this type of transmission. A planned comparison with the *Malhotra* model will additionally confirm the accuracy of the simulation. The current results suggest that this model can be considered reliable for analysis in real operating conditions.

3 MALHOTRA MODEL

Following many years of research, numerous mathematical models are now available to determine the efficiency of cycloidal reducers. One of the most commonly used of them was defined by *Malhotra*. It is a rather simple and easily applicable model described in great detail in the references [2,3]. In the further text, only the essential expressions will be presented.

Since the model is based on the work of the friction force in contact points, the total efficiency is determined according to the following expression:

$$\eta_{CR} = \frac{T_{in} \cdot 2\pi - W_f}{T_{in} \cdot 2\pi} \tag{1}$$

where: $\boldsymbol{T_{in}}$ – input torque; $\boldsymbol{W_f}$ – total work of the friction force.

The total work of the friction force $\boldsymbol{W_f}$ includes the friction: in the cycloidal disc bearing, between the cycloidal disc teeth and the central rollers, between the central rollers and their pins, between the output rollers and the cycloidal disc holes and between the output rollers and their pins (Figure 4).

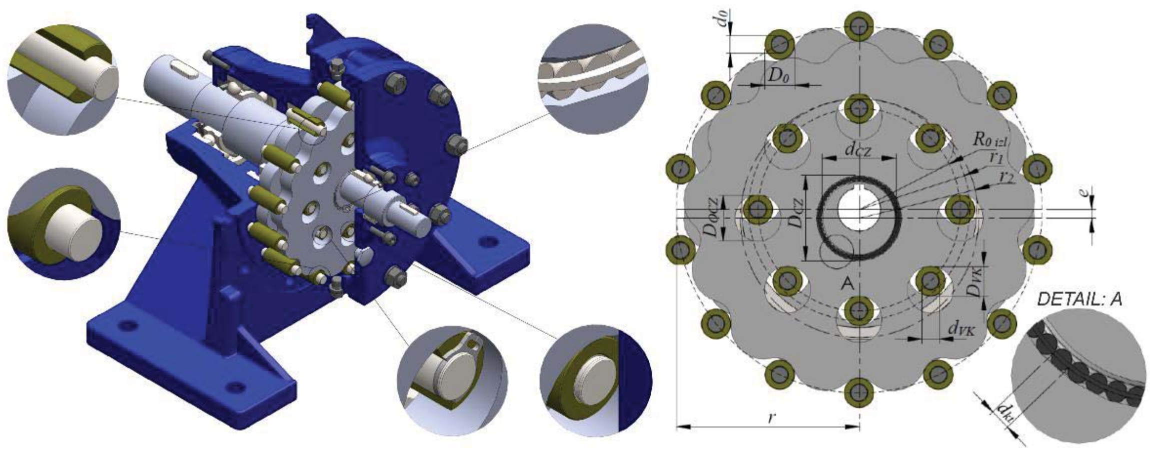

Figure 4. *A classic one-stage cycloidal reducer: a) typical points of mechanical losses; b) geometry of the key elements*

The comprehensive expression obtained by integrating the elementary works $\boldsymbol{dW_f}$ for one revolution of the input shaft can be written in the following form [2,3]:

$$W_f = \frac{f_{r1} \cdot D_{SR} \cdot z_1}{d_{kt}} \int_0^{\frac{2\pi}{z_1}} F_E(\beta) \cdot d\beta + z_1 \cdot \left(f_{r2} + \frac{\mu_{s1} \cdot d_{VK}}{2}\right) \cdot \int_0^{\frac{2\pi}{z_1}} \sum_{j=1}^{q} F_{Kj}(\beta) \cdot d\beta +$$
$$+ (z_1 + 1) \cdot \left(f_{r3} + \frac{\mu_{s2} \cdot d_0}{2}\right) \cdot \int_0^{\frac{2\pi}{z_1}} \sum_{i=1}^{p} F_{Ni}(\beta) \cdot d\beta \tag{2}$$

where: $F_{Ni}(\beta)$ – current value of the normal force on the *i*-th central roller; $F_{Kj}(\beta)$ – current value of the output force on the *j*-th output roller; $F_E(\beta)$ – current value of the eccentric force; f_{r1} – coefficient of rolling resistance of the cycloidal disc bearing, $f_{r1} =$ $= \mu_{r1} \cdot d_{kt}/2$; f_{r2} – coefficient of rolling resistance of the output roller, $f_{r2} = \mu_{r2} \cdot D_{VK}/2$; f_{r3} – coefficient of rolling resistance of the central rollers, $f_{r3} = \mu_{r3} \cdot D_0/2$; μ_{r1} – coefficient of rolling friction in the cycloidal disc bearing; μ_{r2} – coefficient of rolling friction between the output rollers and the holes in the cycloidal disc; μ_{r3} – coefficient of rolling friction between the central rollers and the cycloidal disc; D_{SR} – mean diameter of the cycloidal disc bearing, $D_{SR} = (D_{CZ} + d_{CZ})/2$; D_{CZ} – outer diameter of the cycloidal disc bearing; d_{CZ} – inner diameter of the cycloidal disc bearing; d_{kt} – diameter of the rolling body of the cycloidal disc eccentric bearing; D_0 – diameter of the central roller; d_0 – diameter of the central roller pin; D_{VK} – diameter of the output roller; d_{VK} – diameter of the output roller pin; p – current number of the central rollers participating in the load transfer process (if the total number of central rollers p is an even number, then $p = z_2/2$, and if it is an odd number, then $p = (z_2 + 1)/2$); q – current number of the output rollers participating in the load transfer process (if the total number of output rollers u is an even number, then $q = u/2$, and if it is an odd number, then $q = (u - 1)/2$).

4 COMPARATIVE ANAYISIS OF THE EFFICIENCY

For the comparative analysis of the efficiency obtained using the *CycloidalDrive* block in the Simulink environment and the *Malhotra* mathematical model, a single-stage 6 *kW* cycloidal reducer was used. The basic characteristics of this cycloidal reducer are shown in Table 1, while the values of the sliding and rolling friction coefficients are adopted from the references [1,2,7,15,16], and their values are shown in Table 2.

Table 1. *Basic characteristics of the cycloidal reducer*

Parameter	Unit	Value
Number of the cycloidal disc teeth	-	11
Number of the ring gear rollers	-	12
Diameter of the ring gear roller	*mm*	12
Diameter of the ring gear pin	*mm*	7
Moment of inertia of the input shaft with eccentric sleeve	*Kg·mm*^{2}	8
Moment of inertia of the output mechanism	*Kg·mm*^{2}	100

Table 2. *Adopted values of the sliding and rolling friction coefficients [1,2,7,15,16]*

μ_{r1}	$\mu_{r2} = \mu_{r3}$	$\mu_{s1} = \mu_{s2}$	μ_{s3}
0.005	0.0045	0.05	0.04

The comparative analysis is based on quantification of the individual operating parameters and their influence on the cycloidal reducer efficiency. The first simulation, shown in Figure 5a, includes the change in the output shaft load at constant input speed. In contrast, the second simulation, shown in Figure 5b, focuses on the change in the input shaft speed at constant output shaft load.

The dependence of the efficiency η_{CR} on the load T_{out} at constant input speed n_{in}=1500 min^{-1} is shown in Figure 5a. The load varies in the range from 300 to 400 *Nm*. As the load increases, the efficiency of the cycloidal reducer also increases. According to the Simulink model, the efficiency has increased from 0,902 to 0,940, and according to the *Malhotra* mathematical model, it has increased from 0,915 to 0,941. The biggest difference between the efficiency values is 2,4%.

The dependence of the efficiency η_{CR} on the input speed n_{in} at constant load T_{out} is shown in Figure 5b. The input speed varies in the range from 580 to 1450 min^{-1}. With an increase in the input speed, the efficiency of the cycloidal reducer decreases. According to the Simulink model, the efficiency decreases from 0,950 to 0,940, and according to the *Malhotra* mathematical model, it decreases from 0,949 to 0,941. The biggest difference between the efficiency values is 0,1%.

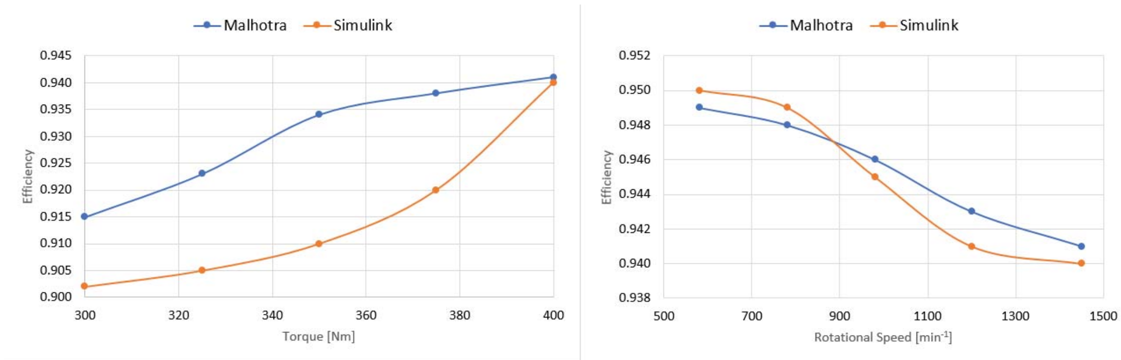

Figure 5. *Comparative results of the efficiency (Malhotra and Simulink model): a) Change in the torque; b) Change in the speed*

5 CONCLUSION

This paper analyses the efficiency of a cycloidal reducer using the new *CycloidalDrive* block in Simulink. The performed simulations have shown that this model covers a variety of operating conditions. The differences in results between the Simulink model and the *Malhotra* model range from 0,1% to 2,4%, which confirms the high reliability and precision of the Simulink model.

The Simulink model has proven to be a reliable tool for analysis of the cycloidal reducer efficiency, providing results in line with expectations. Its ability to simulate different operating conditions makes it particularly useful for further research and industrial applications.

A further improvement of this model can be achieved by creating more accurate simulations of complex phenomena such as friction or by reducing differences in results for certain operating conditions. Moreover, the addition of extra blocks that would simulate the effects of temperature on efficiency could further improve the accuracy and reliability of the model. The development of the Simulink model in this direction would enable even greater accuracy and wider usage of this model in analysis and optimization of cycloidal reducers in various industrial applications.

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