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Computational studies on cycloidal gearboxes: a systematic literature review

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Computational studies on cycloidal gearboxes: a systematic literature review

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Abstract. The high compactness of cycloidal gearboxes, their low backlash and their capability to withstand overloads are just some of the factors that have led the research to focus on these solutions for reducing speed. These types of gearboxes have very complex geometries, architectures and dynamics, and the contact between the various components occurs simultaneously in different areas of them. Therefore, numerical simulations can represent an essential tool for the design of these systems. The objective of this study is to understand in what and how numerical simulations can support the design of cycloidal reduction systems and make a review of the literature to understand to date, who, why and how has conducted these of studies. The reviewed contributions, collected through Scopus, are analyzed and classified according to, among others, the component modelled and analyzed, the scope of the analysis and if the analysis has been validated with experimental results. Bibliometric analyses show that the topic is of growing interest to the international scientific community but remains almost an Asian monopoly since most of the results are not shared in English. It has emerged that the study of the contact between cycloidal disk and rollers remains the most widespread study. The research showed that only a small number of analyses have been validated by experimental results.

1. Introduction

Cycloidal speed reducers embody four main components, as clarified in Figure 1: an eccentric shaft, through which the input motion is provided, a cycloidal disk, the ring gear pin with rollers on which the cycloidal disk engages, and a mechanism that extracts the rotation motion of the cycloidal disk (usually hole-pin).

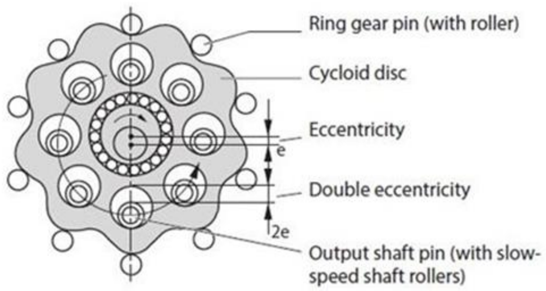

Figure 1. Cycloidal Gear [2]

The input shaft moves the center of the cycloidal disk along a circular trajectory, providing the revolution motion. Following this trajectory, the cycloidal disk meshes on the rollers located on the casing, rotating in the opposite direction to that of the shaft since the number of rollers is greater than the number of lobes. Usually, holes realized inside the cycloidal disk drag pins during the rotation motion, allowing the output shaft to extract this motion and transmit it as the output motion. Naturally, different configuration of cycloidal speed reducers can be designed e.g. by inverting the relative position of the rollers and the cycloidal profile [1].

This system is dynamically unbalanced since the center of mass moves eccentrically and many design solutions were proposed to balance this system e.g. by adding mass, using a counterweight to be mounted on the shaft [3] or by exploiting another cycloidal disk 180° out of phase with respect to the first one [4]. Through the latter solution, it is possible to distribute the forces on two cycloids and therefore improve the performance in terms of power transmission and/or service life of components. The Gear Ratio (GR) can be expressed as in Equation 1 [5]. Here, Z1 is the number of lobes of the cycloidal disk and Z2 is the number of rollers.

$$GR = \frac{\omega_{input}}{\omega_{output}} = \frac{Z_1}{Z_2 - Z_1} = \frac{Z_1}{\Delta} \tag{1}$$

It is therefore easy to infer that the highest GR is obtained when the difference Z2-Z1 (Δ) is minimal, and in the case of cycloidal gearboxes, it is possible to reach the difference of one tooth only [5].

The rolling contact between the cycloidal disk and the rollers is the main factor influencing the efficiency of the gearbox [6]. The various sources of power loss in a cycloidal gearbox is the friction between the rollers and the disk, the friction between holes and pins and the friction in the bearings. If the rollers are not free to rotate, the cycloid efficiency is a function of the circumference of the cycloid disk [7]. The rollers can be made with sliding or ball bearings (non-compact solution) in order to reduce any tangential force due to friction and machining errors (increasing the efficiency) or they can be made integral to better resist shocks and overloads [7].

Theoretically, in cycloidal speed reducers all the lobes are simultaneously in contact with the rollers and half of them are able to transmit torque [8]. Therefore, cycloidal speed reducers are capable of transmitting very high torques and can withstand short-term overloads of up to 500% [8]. This capacity of cycloidal reducers is also because, during the loading, in these profiles there are no tensile (or bending) stresses but only compressive one [9].

The profile of a cycloidal gear set, with a unitary difference between number of rollers and number of lobes, can be expressed by the coordinates C_x and C_y (with the origin in the center of the cycloid) as function of the parameter ϕ (angle of input shaft) that vary between 0 and 2π (Equation 2, 3 and 4) [5].

$$C_x = \mathrm{R} \cdot \cos(\phi) - R_r \cdot \cos(\phi + \psi) - \mathrm{e} \cdot \cos\big((Z_1 + 1) \cdot \phi\big) \tag{2}$$

$$C_y = -\,\mathrm{R} \cdot \sin(\phi) + R_r \cdot \sin(\phi + \psi) + \mathrm{e} \cdot \sin\big((Z_1 + 1) \cdot \phi\big) \tag{3}$$

$$\text{where} \qquad \psi = \tan^{-1}\left(\frac{\sin(Z_1 \cdot \phi)}{\cos(Z_1 \cdot \phi) - \frac{\mathrm{R}}{\mathrm{e} \cdot (Z_1 + 1)}}\right) \tag{4}$$

Where, R is the distance between the centre of each roller and the input shaft axis, R_r is the radius of rollers, e is the eccentricity of the input shaft and Z_1 is the number of lobes of the cycloid (one less of the number of rollers in this case) [5] .

The many construction variants of this type of speed reducer, their complex dynamics and geometries, and the many simultaneous contact zones have led to many numerical simulations to support the design of the various components. Therefore, the aim of this paper is to collect (and discuss) systematically the scientific papers aimed at numerically simulate cycloidal speed reducers (or their specific components) in order to obtain results on tensional stresses, deformation and power losses.

2. Material and method

In order to conduct a systematic literature search, the Scopus database was queried. More specifically, limiting the search in the subject area of engineering, the following keywords were searched in the title, abstract and keywords.

[Cycloid* & (Gear* + Reduc* + Drive) & ("Stress Analysis" + "Numeric* Simulat*" + FEM + FEA + "Finite Element")]

The symbol * allows to include all the suffix e.g. gear* allows to include in the search gear, gearing, gearbox, gearboxes and so on. The symbols & and + are the Boolean operator AND and OR respectively. While, the search of exact words is represented by "".

Through this query has been possible to collect systematically the scientific contributes in which the numerical simulation and/or the Finite Element Analysis of cycloidal speed reducers were conducted. The search has highlighted 149 scientific contributes and, after a first screening by reading the title, the abstract and, when available, the results, 50 articles relevant to the purposes of this research have been identified. Most of the paper emerged were discarded because they study cycloidal gear as pump or wind turbines. Other study the cycloidal profile as alternative of the involute profile in ordinary meshing. Other papers were discarded because they exploit analytical method considering rigid bodies instead of numerical ones.

The pertinent papers have been classified based on:
- The document type i.e. journal article or conference paper;
- The year of publication;
- The number of citation (in Scopus index) until July 2020;
- The country in which the authors' affiliation is based;
- The availability of the full text in English;
- The component modelled and analysed;
- The scope of the analysis;
- If the results of the analysis have been validated with experimental results.

3. Results and discussions

In Table 1 and Table 2, it is possible to see the classification of each pertinent paper. In the tables, the paper are ordered based on the year of publication i.e. from oldest to the newest. The paper are homogeneously published in conferences and journals; 26 in conferences and 24 in journals.

3.1. Bibliometric results

Table 1. Bibliometric results

Reference	Year	Country	Journal / Conference	Citations on Scopus	English Full Text Available
[10]	1996	Japan	Journal	6	No
[11]	1996	Japan	Journal	11	No
[12]	1998	Japan	Journal	3	No
[13]	2001	China	Journal	7	No
[14]	2001	China	Conference	0	No
[15]	2008	China	Conference	1	Yes
[16]	2009	South Korea	Journal	5	No
[17]	2010	China	Journal	1	No
[18]	2010	China	Journal	15	No

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[19]	2010	South Korea	Conference	6	Yes
[4]	2011	Serbia	Journal	58	Yes
[20]	2011	China	Conference	0	Yes
[21]	2011	United States	Conference	4	Yes
[22]	2011	China	Conference	2	Yes
[23]	2011	China	Conference	1	Yes
[24]	2011	China	Conference	0	Yes
[25]	2011	China	Conference	1	Yes
[26]	2012	China	Conference	2	Yes
[3]	2012	United States	Conference	5	Yes
[27]	2012	China	Conference	0	Yes
[28]	2012	China	Conference	0	Yes
[29]	2013	China	Journal	3	No
[8]	2014	Serbia	Journal	8	Yes
[30]	2014	Japan	Journal	40	Yes
[31]	2014	China	Conference	0	Yes
[32]	2015	China/United States	Conference	0	Yes
[33]	2015	China	Conference	0	Yes
[34]	2015	China	Conference	0	No
[35]	2015	Taiwan	Conference	7	No
[36]	2017	China	Journal	1	No
[37]	2017	China	Journal	6	No
[38]	2017	Netherlands	Journal	5	Yes
[39]	2017	China	Journal	0	No
[40]	2017	China	Conference	3	Yes
[41]	2017	China	Conference	4	Yes
[42]	2018	China	Journal	3	No
[43]	2018	China	Conference	0	Yes
[44]	2019	China	Journal	0	No
[45]	2019	Poland	Journal	1	Yes
[46]	2019	China	Journal	1	Yes
[47]	2019	China	Journal	3	Yes
[48]	2019	Taiwan	Journal	0	Yes
[49]	2019	Taiwan	Conference	0	Yes
[50]	2019	Italy	Conference	4	Yes
[51]	2019	China	Conference	0	Yes
[52]	2019	China	Conference	0	Yes
[53]	2019	China	Conference	0	Yes
[54]	2020	China	Journal	0	No

[55]	2020	China	Journal	0	No
[56]	2020	Italy	Journal	0	Yes

In Figure 2, the amount of relevant papers published over the years is reported. It is possible to notice the increase interest in the last decade to this research topic.

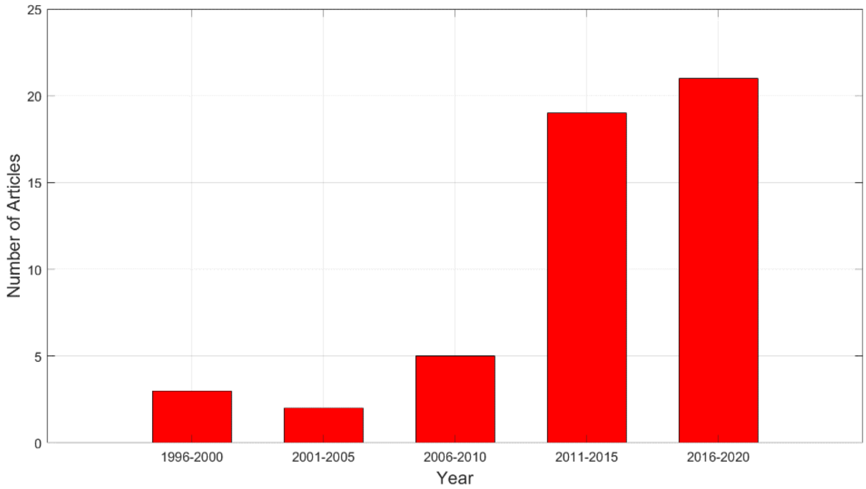

Figure 2. Distribution of relevant publications over the years

In Figure 3, it is possible to notice the distribution of the relevant publications over the country and then over the continents. In this analysis, it is clear that the proposed research topic has been mainly addressed by Asian universities (more than the 82% of the relevant papers), in particular Chinese universities (more than the 64% of the relevant papers). The high interest of the Asian researchers in this topic also leads to a difficult availability of the full texts of the publication in English. Indeed, the authors were not able to find the full text in English of 18 (out of 50) papers.

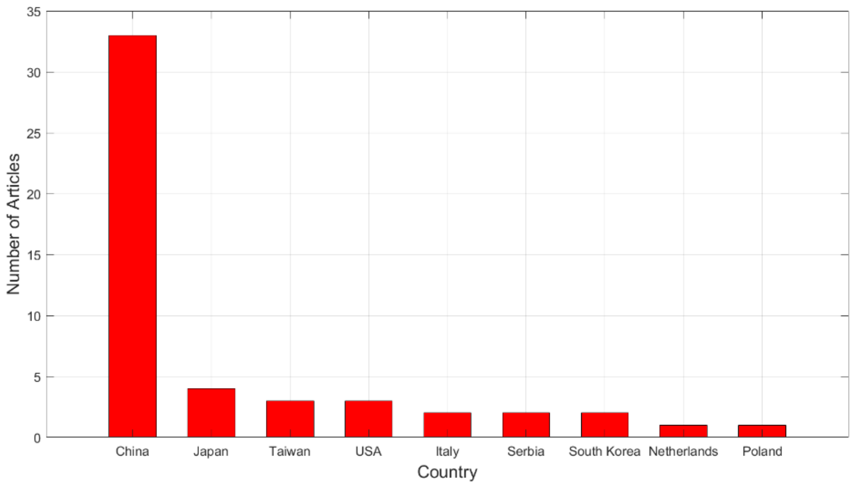

Figure 3. Distribution of relevant publications over the country

To date, the most cited papers are indisputably [4] with 58 citations and [30] with 40 citations. In [4], an innovative solution is presented and studied numerically and experimentally. In [30], a method for building the geometrical and the finite element model of the cycloidal disk is presented.

3.2. Technical results

Table 2. Technical results

Reference	Component Modelled and Analyzed	Scope of the Analysis	Validation with experiment
[10]	Cycloidal Disk	To obtain the normal contact forces and contact stress	No
[11]	Cycloidal Disk	To obtain the normal contact forces and contact stress	No
[12]	Cycloidal Disk	To obtain the normal contact forces and contact stress	No
[13]	Cycloidal Disk and Rollers	To verify the applicability of a new solution	No
[14]	Whole System	To verify the applicability of a new solution	No
[15]	Whole System	To obtain the shear stress distribution	No
[16]	Cycloidal Disk	To study the torsional stiffness	Yes
[17]	Whole System	To verify the applicability of a new solution	No
[18]	Cycloidal Disk and Roller balls	To obtain the stress distribution on the contact area	No
[19]	Cycloidal Disk	To study the torsional stiffness	Yes
[4]	Whole System	To verify the applicability of a new solution	Yes
[20]	Rollers	To obtain the torsional stiffness	No
[21]	Whole System	To obtain the stress state of the cycloidal disk, pins and rollers	No
[22]	Whole System	To study the transmission error	No
[23]	Cicloidal Disk and Pins	To validate an analytical model	No
[24]	Rollers	To obtain the stress on (modified) rollers	Yes
[25]	Cycloidal Disk and Roller balls	To study the variation of thermo-mechanical coupling contact stress of engagement pair at maximum force position with working temperature	No
[26]	Cycloidal Disk and Rollers	To validate an analytical model	No
[3]	Whole System	To obtain the stress state of the cycloidal disk, pins and rollers	No
[27]	Cycloidal Disk and Rollers	To obtain the stress state of the cycloidal disk and rollers	No

[28]	Cycloidal Disk and Pins	To obtain the stress and deformation of the dowel pin	No
[29]	Cycloidal Disk and Rollers	To obtain the normal contact forces, friction forces, and contact stress	No
[8]	Cycloidal Disk	To obtain the stress state of the cycloidal disk for the most critical case of the meshing	Yes
[30]	Cycloidal Disk	To obtain the stress state of the cycloidal disk	No
[31]	Whole System	To obtain the normal contact forces, friction forces, and contact stress	No
[32]	Cycloidal Disk and Rollers	To validate an analytical model	No
[33]	Cycloidal Disk and Rollers	To study the lubrication	No
[34]	Whole System	To perform a modal analysis	No
[35]	Whole System	To verify the applicability for a case study	Yes
[36]	Cycloidal Disk and Rollers	To study the temperature distribution	No
[37]	Whole System	To study the transmission error	No
[38]	Cycloidal Disk and Rollers	To study the power losses and stiffness of a new solution	Yes
[39]	Whole System	To perform a modal analysis	No
[40]	Cycloidal Disk and Rollers	To study the impact on meshing force caused by the gap due to manufacturing error of the rollers	No
[41]	Cycloidal Disk and Rollers	To obtain the normal contact forces, friction forces, and contact stress	No
[42]	Cycloidal Disk and Rollers	To study the time-varying meshing stiffness and load distribution	No
[43]	Whole System	To find the most stressed area of the cycloidal disk	No
[44]	Cycloidal Disk and Rollers	To study the effect of profile modification due to machining errors on load distribution and contact stress	No
[45]	Whole System	To obtain the torque ripple on the output shaft	Yes
[46]	Cycloidal Disk	To obtain the normal contact forces, friction forces, and contact stress in order to optimize the geometrical parameters	Yes
[47]	Cycloidal Disk and Rollers	To obtain the torsional stiffness based on cycloid parameters	Yes
[48]	Whole System	To study the dynamic forces and failure characteristics	No

[49]	Cycloidal Disk and Rollers	To study the effect of profile modification on load distribution and contact stress in order to optimize the modified profile	Yes
[50]	Whole System	To predict power losses due to fluid-structure interaction	No
[51]	Whole System	To obtain the stress and deformation of the cycloidal disk, rollers and eccentric shaft	No
[52]	Whole System	To optimize the geometrical profile based on the minimum stress	No
[53]	Whole System	To obtain the stress and deformation of the cycloidal disk, rollers and eccentric shaft	No
[54]	Cycloidal Disk and Rollers	To study the influence of the thickness of the cycloidal disk on meshing characteristic and to obtain the torsional stiffness	No
[55]	Cycloidal Disk and Rollers	To obtain the normal contact forces, friction forces, and contact stress	No
[56]	Cycloidal Disk and Rollers	To obtain the normal contact forces, friction forces, and contact stress in order to verify (and optimize) a new configuration	No

In Table 2, it is possible to notice that the component modelled and analysed through finite elements or volumes can be classified in six categories i.e. Cycloidal Disk only, Rollers only, Cycloidal Disk and Rollers, Cycloidal Disk and Roller balls, Cycloidal Disk and Pins, Whole System. However, in the most of the simulations, either the entire system or the most critical elements of the contact (i.e. the cycloidal disk and rollers) are modelled and discretized by finite elements.

In Figure 4, it is possible to see the distribution of the scope of the analysis.

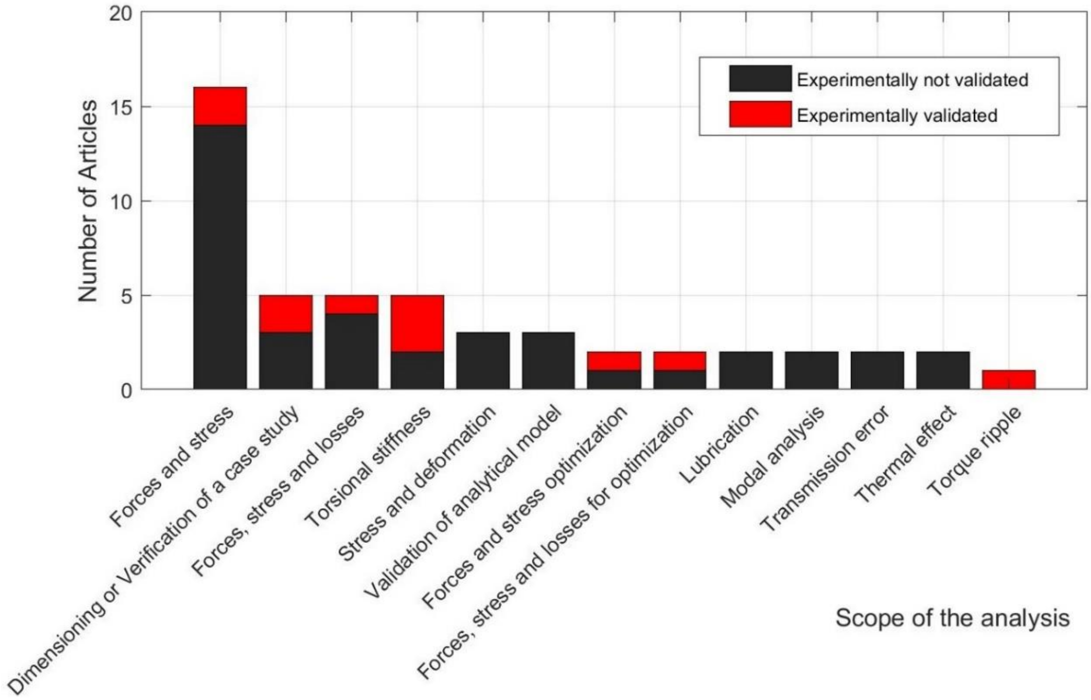

Figure 4. Distribution of the scope of the analysis divided by articles that have been experimentally validated (in red) and those that have not (in black)

In this histogram it is possible to see that most of the studies aim to obtain a map of the stress and/or to get the forces transmitted to the various rollers. In some cases these analyses have been used to verify the strength of new architectures for specific case studies. In other studies the aim is also to obtain losses, in others to understand the torsional stiffness or general deformations. Some studies aim to validate analytical models, others to optimize geometries. Others scholars study losses due to lubrication, thermal effects, vibrations and torque oscillation. However, it is interesting to note that the 78% of these analyses are not accompanied by experimental validation. In particular, the articles that included the experimental validation aimed at studying the torsional stiffness and the torque ripple.

4. Conclusions

In conclusion, a systematic analysis of the literature through Scopus of the contributions that study the numerical simulation of cycloidal reduction systems has been carried out in this work.

From the bibliometric analyses it emerges that the topic is of growing interest to the international scientific community but it remains almost an Asian monopoly since most of the results are not shared in English.

It has emerged that different modelling strategies have been adopted to study the various components with different objectives but the study of the contact between cycloidal disk and rollers remains the most widespread study. However, no standard approaches have been unanimously shared by researchers.

The research also showed that only a small number of analyses have been validated by experimental results.

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