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BENEFITS OF THE APPLICATION OF CYCLOIDAL BACKLASH GEAR REDUCERS WITH MORE ECCENTRIC SHAFTS

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ABSTRACT. Backlash gear reducers belong to mechanisms that are now increasingly used in mechanical engineering, first of all in machine tools for accurate positioning of tools while processing, in measuring machines, scanners and radars, where they are used for accurate transmission of motion, in robotics, where used for accurate positioning of nippers and other working organs, and especially in military field of mechanical engineering (with artillery tools and rocket launchers), where there are used to capture the exact elevation angle and azimuthal angle, aviation, etc. As is known, backlash gear reducers include all reducers with arc gap of less than 10 arc minutes, although for more accurate positioning (1 m to 1 km) arc gap is only slightly greater than 3 arc minutes. This paper analyzes universal cycloidal backlash gear reducers with more eccentric shafts and it was concluded that an increased number of shafts can significantly raise backlash and self-locking, that is for this kind of reducers extremely important.

KEYWORDS. cycloidal, backlash, reducer, more, eccentric shaft

1. INTRODUCTION

Backlash gear reducers are mechanisms designed for transmission of mechanical energy and motion, from driving to working machine, while they are used to reduce number of revolutions and to increase torque, and in some cases, they are used to change direction of rotation and to change the position of the driving machine shaft axis. Backlash gear reducers today have greater application in mechanical engineering, due to the fact that driving machines (engines) are usually driven by electric motors which usually work with a significantly higher number of revolutions than working machines, so reducers are used to adjust the number of revolutions and torque of driving machine to requirements of working machines (KUZMANOVIĆ, S. 2009). Backlash gear reducers are transmitters of motion.

2. THE BASIC CLASSIFICATION OF CYCLOIDAL BACKLASH GEAR REDUCERS

Cycloidal backlash gear reducers are usually categorized by the number of used records on cam:
- reducers with a single cam (overhead panel),
- reducers with twin cam plate and
- reducers with three plates.

Depending on the number of eccentric shafts, cycloidal reducers are divided into:
- gear with a single eccentric shaft,
- gear with two eccentric shafts and
- gear with three eccentric shafts.

Depending on the size of the arc gap $\Delta \varphi_z$, there are:
- backlash gear reducers, with the angular gap $\Delta \varphi_z \leq 10^\circ$ per gear pair,
- low backlash gear reducers, with the angular gap of $\Delta \varphi_z \leq 1^\circ$ per gear pair and
- industrial gear reducers, with the so-called normal gap with $\Delta \varphi_z > 1^\circ$ (Ondrive Precision Manufacturing).

Here only cycloidal backlash gear reducers will be considered.

3. DEFINITION OF BACKLASH REDUCERS

For the proper functioning of the gear reducers, it is necessary that there is a certain gap between cogs, i.e. that the width of the space between cogs is slightly larger than the width of the cog of coupled gears. The clearance is necessary in order to avoid interference, wear and overheating of cogs, to enable proper lubrication, to compensate deviations in production and to enable thermal expansion. Thereby, it should be noted that there is a gap in the roller bearings, which can also affect the increase of the clearance between cogs.

In the classical reducers the value of that gap is not so important, while in backlash gear reducers it is extremely important and seeks to be reduced to the lowest possible level (Ognjanović, 2000).

Small gap between cogs, in backlash gear reducers, is needed to ensure high positioning accuracy, where the positioning accuracy means the difference between the expected and actual position of the output shaft. As the gear has circular shape, the gap appears as angular size, i.e. as the arc gap.

Arc gap $\Delta \varphi_z$ is the angle of rotation of the output shaft,
if the input shaft is fixed, i.e. it is stationary, and its value is expressed in arc minutes. In case that the value of this angle is less than 10 arc minutes the reducer is considered as backlash reducer.

It should be noted that the gap in gear pair is just a part of idle motion, which describes a condition in which, based on the mechanism input, does not get any response at the output.

Idle motion $\Delta \phi_0$ of gear reducers is the output shaft rotation angle of the gear reducer under load with a torque $T$, at full cycle of changes in torque and at fixed input shaft (Fig. 2). It is the sum of the arc gap and the elastic torsion deformation of the shaft.

The rigidity of cogs, especially the torsion rigidity of the shaft, strongly influences the size of the idle motion of backlash gear reducers and therefore it seeks to increase the rigidity by adopting larger modules, shorter shafts and larger shaft diameters.

The graphic representation of values of the idle motion is given in Fig. 1. Although, at present, there is no standard that defines the way of measuring the load, it is usually measured on the output shaft since its value is then much smaller (because of the larger gear diameter) and thereby certainly more interesting for display. The unit for measuring the arc gap, as already stated, is arc minute.

![Fig. 1. Graphic representation of idle motion changes with changing loads (NEUGART)](image)

Theoretically speaking, there is no torque required to register gap, i.e. it does not depend on the load. However, in reality, it’s not the case, because in order to overcome the internal friction in the reducer and to eliminate the gap between the coupled elements, a certain torque is required. With increasing torque components deform elastically, leading to an increase of the idle motion, which is registered on the output shaft as the rotation angle which depends on the load, and its size is a measure of the rigidity of the reducer.

In reality, changing the load looks a little different (Fig. 2). After a certain amount of torque required eliminating all gaps in the system, it is practiced to amend the complete cycle of gear load change (from zero to nominal load in one direction, then reducing the load and changing the torque in the other direction, to nominal value). In this way the "hysteresis loop" of the reducer is generated that enables to determine not only the actual gap, but the torsion rigidity of the reducer and the idle at any load.

Because of the elasticity of the shaft and gear cogs, the idle motion of the backlash gear reducer is not in the form of straight line, but in the shape of the curve, covering a slightly wider field (Fig. 2). The initial values of arc gaps appear at the torque whose value is typically only 2% of the nominal value of torque.

The actual value of the arc gap for precision servo systems with a small arc gap typically ranges from 2 to 8 arc minutes (measured at the output).

Torsion rigidity (or its reciprocal value - the elasticity) is the size of the elastic angular deformation, which occurs on the output shaft under load, due to elastic deformation of gears and shafts. The rigidity and elasticity were determined on the basis of the measured deformation and the load of the reducer (Fig. 2). Rigidity shows what torque is required for unit value of deformation. A common unit for the rigidity: Nm /arc min. Elasticity indicates what deformation torque creates. A common unit for elasticity is arc min /Nm.

Most of the idle motion occurs due to the elasticity of the cycloidal reducer components. For high accuracy positioning rigidity effects cannot be ignored.

![Fig. 2. Graphic representation of the real change of the idle motion of backlash gear reducers (NEUGART)](image)
rigidity of the system and dynamic response, so it is necessary to consider its properties when choosing it, because the market offers couplings in different variants, with different rigidity and damping capabilities.

4. CYCLOIDAL REDUCERS

4.1. Introduction

Despite their high prices, cycloidal reducers face (encounters) great application in mechanical engineering because of the extremely small gap, a long period of holding such a small gap (due to the large number of cogs in mesh), because of the possibility of transferring high torque and high gear ratios (Kuzmanović and Vereš, 2006; Kuzmanović and Rackov, 2009). They are available in three basic variants with one, two and three eccentric shafts.

4.2. Cycloidal gear reducers with one (a single) eccentric shaft

Cycloidal gear reducers with one eccentric shaft (Fig. 3) in spite of high accuracy, have a slightly lower accuracy from reducers with two and three eccentric shafts.

Fig. 3. Characteristic solution of the cycloidal backlash gear reducer with a single eccentric shaft (SUMIMOTO DRIVE)

The working principle of this reducers is pretty simple. The input shaft typically has two eccentric, with one cam plate on both of them. Cams are identical and two are used to repeal the radial forces that occur at the contact which enables quieter operation. This ensures a longer and larger contact of the coupled cogs and increases rigidity and enables backlash easier. The rotation of the eccentric shaft causes the coupling of cam plates with rollers which are placed along the rim of the circle, which causes cam plate rolling by rollers. This complex movement of cogs is taking over by rollers, which are placed in specially drilled holes in the cam plates, which are an integral part of the output shaft. So, rolling the cams by rollers causes the rotation of the output shaft (Fig.4).

Fig. 4. Schematic representation of the working principle of the cycloidal backlash gear reducer with a single eccentric (Sumimoto Drive)

Reducers are used with one, two and three cam plates. The increase of the number of records causes the increase of the accuracy and load and, unfortunately, the price of the gear. For less demanding drives cycloidal backlash gear reducers with just a single cam (overhead panel) are used.

4.3. Cycloidal reducers with two eccentric shafts

Cycloidal reducers with two eccentric shafts (Figure 5) are slightly different from the classical cycloidal reducers, but are able to provide greater accuracy and less arc gap. Cycloidal reducers have very compact design.

Fig. 5. Assembly drawing of the cycloidal backlash gear reducer with two eccentric. The rotation direction of the output shaft is the same as the input rotation (NABTESCO)

The working principle is very similar to cycloidal reducers with one eccentric, except that the application of two eccentric shafts allows to transmit more torque, and achieves a greater accuracy (Fig. 6 a and b). Namely, the torque from the input shaft through the cylindrical backlash gears is transferred to the two eccentric shafts (Fig. 6 a), from which the movement is transferred to the cam plate (Fig. 6 b), which performs complex rolling by rollers, which are circular placed along the edge of the housing. This complex movement is taken through the same two eccentric shafts, which are molded into the two front panels that are connected via two lunate parts which together represent the output shaft (Fig. 7).
positive effect on reducing arc gap.

**Fig. 6.** Representation of the way of starting the eccentric shafts (1) and the way of moving cams (2) in the cycloidal backlash gear reducer with two eccentric (NABTESCO)

**Fig. 7.** Schematic representation of the working principle of the cycloidal backlash gear reducer with two eccentric (NABTESCO)

### 4.4. Cycloidal reducers with three eccentric shafts

Cycloidal reducers with three eccentric shafts (Fig. 8) achieve even greater backlash and capacity.

Cycloidal reducers with three eccentric work on a similar principle as cycloidal reducers with two eccentric shafts. From the input shaft through a planetary backlash gear reducer (Fig. 9) all three eccentric shafts are driven simultaneously. The number of shafts i.e. gears in conjunction has very

**Fig. 8.** A characteristic solution of the special cycloidal backlash gear reducer (NABTESCO)

**Fig. 9.** The schematic representation of the driving principle of eccentric shafts in the cycloidal backlash gear reducer with three eccentric (NABTESCO)

Eccentric shafts move cam plates (Fig. 10) and roll them on rollers which are placed along the edge of the housing.

**Fig. 10.** The schema of the rolling of cams on rollers in cycloidal backlash gear reducer with three eccentric shafts (NABTESCO)

This complex movement which is now much more accurate due to three supports (eccentric shafts) is transmitted through the same three eccentric shafts which are supported in the two front plate molded in the housing of the reducer and interconnected with three outlets in a trapezoid shape (Fig. 11).
5. CONCLUSIONS

Backlash reducers are just one of the components of a propulsion (drive) system which includes an electric motor with brake, a counter of the number of revolutions (rev counter) and a processor also. Because of demands for accurate positioning, backlash reducers today have greater application in mechanical engineering. The demand for a compact structure, in order to use the available space more rational and to reduce weight of the whole system, caused the increased use of cycloidal reducers today. Small clearances between cogs and high torsional rigidity of shafts provide precision, exact position, repeatability and high reliability of such reducers. In places requiring high rigidity of the system, especially in places where there is a "contra-torque", which is often the case in mechanical engineering, cycloidal reducers are used because they are very rigid and self-locking, so, due to the high torque on the output, there will be no movement of the taken position of the output shaft.

Certainly, great positioning accuracy, which ranges below 3 arc minutes, especially contributes to their implementation. The main characteristic of the cycloidal reducers is a long life (ie, a long period of backlash retention) as a result of the large number of cogs in cut and a large number of cam plates (today usually three). Cycloidal reducers despite the extremely high prices, especially those with three eccentric shafts, are of great use in the most responsible systems, where beside the high precision of position taking, a high degree of repeatability is also required. On less responsible places other types of backlash reducers are used.

Fig. 11. Assembly drawing of the cycloidal backlash gear reducer with three eccentric shafts (NABTESCO)

Fig. 12. The schematic representation of the driving principle of eccentric shafts in the cycloidal backlash gear reducer with two and three eccentric shafts (NABTESCO)

After examining the catalogues it is evident that arc gap values are moving within limits of 6 arc minutes for cycloidal reducers with two eccentric shafts, while in cycloidal reducers with three eccentric shafts have arc gap about 1 arc minute. Based on this, it can be concluded that the application of cycloidal reducers with three eccentric shafts is justified, especially, because they have greater surface contact, and are able to keep backlash long.

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