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Research paper

COMPARATIVE ANALYSIS OF POWER TRANSMISSION GEARBOXES WITH HIGH GEAR RATIOS

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Abstract: *In modern industrial practice, there is a growing need for power transmission gearboxes with high gear ratios. Until a few decades ago this requirement was solved using conventional gear types (cylindrical, bevel, worm and planetary). The development of science has also resulted in the emergence of new types of power transmission gearboxes (harmonic drives, cycloidal reducers, ...) which are more often used today, especially when high gear ratios are required. Within this paper planetary reducer, cycloidal reducer and harmonic drives are presented. Their basic operating characteristics as well as the field of application in different working conditions are described. Mutual comparison was made from the aspect of dimensions, mass and efficiency for different gear ratios. For this purpose, catalogues of renowned manufacturers of these types of reducers have been used. The advantages of using new generation reducers are presented in this paper. Paper concludes with observations and guidelines for future research in this field were presented.*

Key words: *high gear ratio, cycloidal reducer, harmonic drive.*

1. INTRODUCTION

Transmission gearboxes perform the transformation of power parameters and the movement of the drive machine and adapt them to the needs of the work machine [1]. In practice, the most represented are mechanical transmission devices that transmit power and movement in shape, friction of touch surfaces or a combination of these two modes [2], [3]. Of the mechanical transmission devices, conventional gearboxes have the most practical applications.

Very complex demands of the modern industry in the last few decades have caused intense development in the field of power transmission devices. Requirements are often contradictory, because on the one hand it is necessary to increase its efficiency, portability, flexibility, reliability and, on the other hand, reduce dimensions, price, delivery, … That's why a large number of research in the field of conventional gearboxes is dedicated to achieving these objectives. Analysis of the teeth number influence on the gear module size and load carrying capacity of universal helical gear drive is presented in literature [4]. The optimization of gearbox parameters is also often a modern research topic [5].

In modern industrial practice, there is an increasing need for gearboxes with high gear ratios. This paper presents basic types of gearboxes that can meet this requirement. A comparative overview of their basic performance characteristics (efficiency, dimensions, mass, etc.) is given.

2. GEARBOXES WITH HIGH GEAR RATIOS

To achieve high gear ratios in propulsion systems until a few decades ago, conventional gearboxes (cylindrical, bevel, worm) were used. Their efficiency (except the worm gearboxes) could be very good to meet the set requirements, but their dimensions and mass have increasingly represented the problem and a major obstacle to installation.

Planetary gearboxes have slowly gained market. Their application began in transport and military, and later spread to all other industrial branches. A schematic representation of a planetary gearbox is given in Figure 1.

The advantages of planetary gearboxes are: smooth and quiet operation, high efficiency, high torque transmission, uniform distribution of load on the satellite, ... Their disadvantages are: one degree of transmission is efficient to the transmission ratio 1:10, the wear of gears increases backlash, gear ratios greater than 1:100 requires 3 stages of transmission, ...

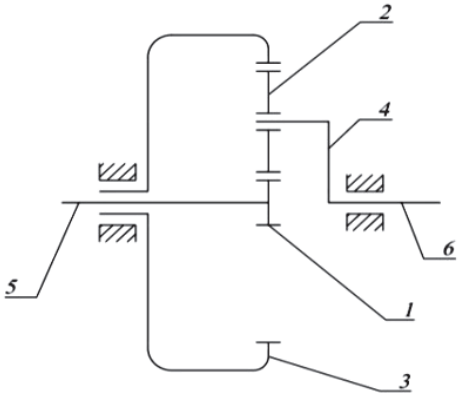

Fig.1. Schematic representation of a planetary gearbox (1- sun gear, 2- planet gear, 3- ring gear, 4- planet carrier, 5- input shaft, 6- output shaft) [6]

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The group of planetary gearboxes also includes cycloidal reducer (Figure 2). These gearboxes are members of the newer generations of gearboxes and differ, primarily, by the type of gearing - cycloidal reducers contain gears with a cycloidal tooth profile. Gears with a cycloidal tooth profile have numerous favorable operating characteristics in a kinematic and dynamic point of view [6,7]. During the meshing, the concave and convex surfaces are in touch, which significantly reduces the contact pressure and wear of the teeth side. In the case of a cycloidal gearbox, the gear ratio is equal to the number of teeth of the cycloidal gear. Precisely because of this, cycloidal reducers have a very wide range of possible gear ratios.

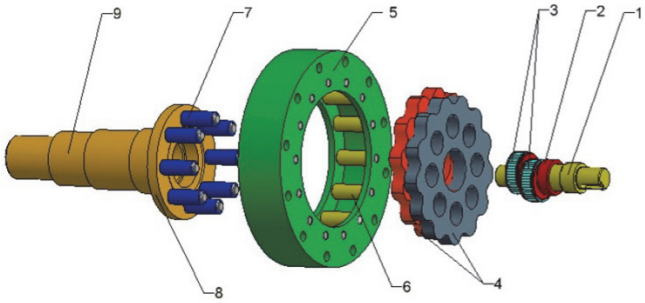

Fig.2. Cycloidal reducer (1- input shaft, 2-eccentric, 3-needle roller bearing, 4- cycloidal gears, 5- ring gear housing, 6- ring gear pins with rollers, 7- output roller, 8- output shaft speed assembly, 9- output shaft) [7]

The advantages of the cycloidal reducer are: sliding friction has been replaced by rolling friction, very low intensity wear, extremely compact design, low backlash, smooth and quiet operation, exceptional dynamic balance, ... The disadvantages are: they are not practical for gear ratios less than 1:30, have a lower efficiency, large external diameter of the reducer, ...

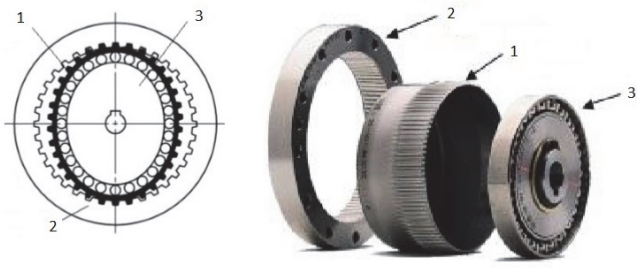

Fig.3. Harmonic drive [9]

In the second half of the 20th century, harmonic reducers appeared [8]. Harmonic reducer is much different from the conventional power transmission devices. Specifically, it uses an elastic component that can be deformed to achieve a high gear ratio. Basically, a harmonic reducer consists of three coaxial elements. These are: flex spline (1), circular spline (2) and wave generator (3), (Figure 3). The flex spline has the shape of a thin-walled cylinder with an external toothing. It is an atypical constructive element that occurs only in this kind of gearbox. The circular spline has circular shape with internal toothing. It is usually hitched to the housing and does not make any movement. The wave generator radially deforms the flex spline, so this gets the shape of an ellipse and make a contact with a circular spline in the direction of the main axis of the ellipse.

The advantages of the harmonic gearbox are: considerably lower mass compared to other types of gearboxes, the input and output shafts are coaxial, belong to a group of low backlash power transmission devices, ... The disadvantage is that they are still not sufficiently explored, and therefore their application is significantly limited.

3. COMPARATION OF THE GEARBOXES WITH HIGH GEAR RATIOS AMONG EACH OTHER

Today in practice, often in front of mechanical engineers - constructors, not a simple task is set: the choice of gearboxes with high gear ratio for a specific industrial application. It is necessary in a very limited time period from a rich market offer, and in accordance with the basic criteria (efficiency, dimensions, mass, price, ...), to choose the optimal solution.

In order to resolve these dilemmas in as highest as possible quality, this chapter provides a comparison of the next-generation gearboxes with high gear ratios.

When planetary reducers and cycloidal reducers are compared, if the main criteria for selecting the gearbox is high precision (low backlash in the gearbox), the cycloidal reducer has the advantage [10]. If a comparison is made on the basis of a gear ratio, different options are possible. If the gear ratio goes to 1:30 cycloidal reducers are rarely used and planetary gearboxes have advantage. In the gear ratio from 1:30 to 1:100, good performance characteristics have both types, but the planetary ones have a smaller mass and dimensions [10]. In the case of high gear ratios, cycloidal reducers are in advantage, all the way to the transfer ratio 1:119 can be performed as single-stage [11,12].

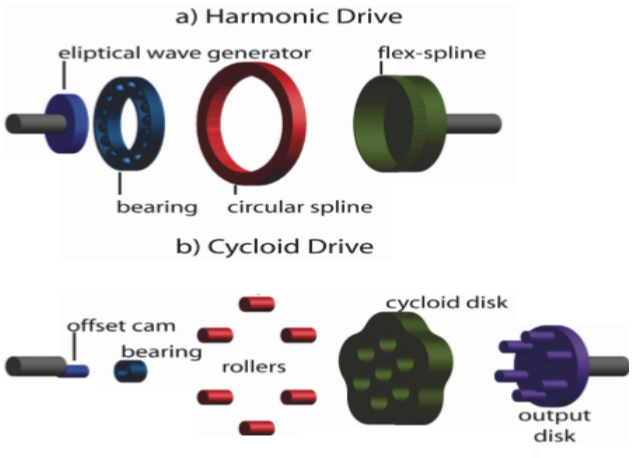

Fig.4. Comparative display: a) harmonic reducer and b) cycloidal reducer [13]

The common feature of single-stage cycloidal reducer and harmonic reducers is that their direction of rotation of the input and output shafts is the opposite. A comparative display of the cycloidal reducer and the harmonic reducer is given in Figure 4. For easier understanding, the

elements with the same functions are marked with the same colors. In the case of a cycloidal reducer, the main element is an eccentric shaft, while in the harmonic, it is a wave generator. In the case of a cycloidal gearbox there is a rolling friction, while in the harmonic sliding friction appears. The cycloidal reducer has better performance characteristics in terms of efficiency, especially at lower torque.

4. ANALYSIS OF THE TECHNICAL CHARACTERISTICS OF THE GEARBOXES WITH HIGH GEAR RATIOS

Within this chapter, a comparison of the basic performance characteristics of the gearboxes with high gear ratios has been performed: conventional, planetary, cycloidal and harmonic [14]. From the catalog of world-renowned manufacturers of these types of gearboxes, their performance characteristics have been taken for the input power of P=3kW and input speed of n_1= 1450 min^{-1}. The gear ratios 1:10, 1:20, 1:50, 1:120, 1:200, 1:300 and 1:400 have been analysed. The meaning of the compared dimensions (A and H) is shown in Figure 5.

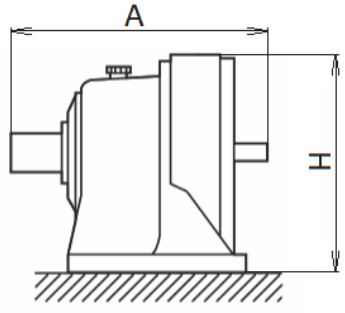

Fig.5. Dimensions of gearbox

The basic operating characteristics of the conventional gearboxes are shown in Table 1, the planetary in Table 2, the cycloidal in Table 3 and the harmonic in Table 4. The meaning of the codes in the table is:

i – gear ratio,
η - efficiency,
n_2 – output speed, (min^{-1}),
m – mass, (kg),
M_2 – output torsional moment, (Nm),
A – length of gearbox, (mm),
H – height of gearbox, (mm).

Table 1. Parameters of the conventional gearboxes –Nord [15]

Designation	i	η	n_2 (min^{-1})	m (kg)	M_2 (Nm)	Number of stages	A (mm)	H (mm)
SK32-100 AH/4	9.80	0.99	145	29.8	197	2	299	292
SK32-100 AH/4	20.70	0.98	69	29.8	416	2	299	292
SK63-100 AH/4	50.73	0.98	28	128.8	1020	3	461	480
SK73-100 AH/4	124.41	0.96	11	209.8	2501	3	531	550
SK73-100 AH/4	205.61	0.96	6.9	209.8	4008	3	531	550
SK 73/22 - 100 AH/4	279.33	0.95	5.1	228.8	5389	5	710	550
SK 83/42 - 100 AH/4	374.99	0.95	3.8	361.8	7234	5	872	639

Table 2. Parameters of the planetary gearboxes -Bonfiglioli [16]

Designation	i	η	n_2 (min^{-1})	m (kg)	M_2 (Nm)	Number of stages	A (mm)	H (mm)
300L1	9	0.97	157	23	170	1	144	193
300L2	20.1	0.94	70	27	380	2	197	193
301L2	51.9	0.94	27.2	30	980	2	267	225
305L3	124	0.91	11.3	56	2270	3	406	282
306L3	205	0.91	6.9	98	3740	3	483	326
306L3	288	0.91	4.9	98	5260	3	483	326
307L4	406	0.88	3.5	143	7180	4	623	374

Table 3. Parameters of the cycloidal gearboxes -Sumitomo [11]

Designation	i	η	n_2 (min^{-1})	m (kg)	M_2 (Nm)	Number of stages	A (mm)	H (mm)
6125	11	0.95	130	24	210	1	274	257
6130	21	0.95	67.9	43	401	1	351	300
6135	51	0.95	27.9	43	974	1	351	300
6160DC	121	0.9	11.8	94	2190	2	463	353
6180DB	195	0.9	7.3	183	3530	2	526	451
6190DA	319	0.9	4.47	241	5770	2	629	531
6195DA	425	0.89	3.35	241	7690	2	629	531

Table 4. Parameters of the harmonic gearboxes - HarmonicDrive [17]

Designation	i	η	n_2 (min^{-1})	m (kg)	M_2 (Nm)	Number of stages	A (mm)	H (mm)
CSF-80-50-2	50	0.78	29	12.4	770	1	101	265
CSF-90-120-2	120	0.74	12.08	17.6	1650	1	112.5	300
FR-80-194-2	194	0.48	7.47	22.3	1840	1	83	265
FR-100-320-2	320	0.35	4.53	42.6	2719	1	101	330

Based on the data taken from the manufacturer's catalogues of the analysed gearboxes (Tables 1-4), a comparison of their most important performance characteristics has been made.
Figure 6 shows the dependence of the mass of the gearbox in relation to gear ratio. The largest masses have conventional gearboxes, and the smallest harmonic, with the note that the application of harmonic reducers is limited in the gear ratio range 1:50 to 1:300.

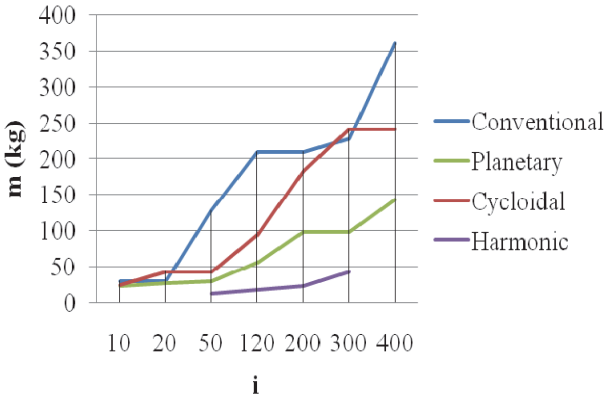

Fig.6. Dependence of the mass of the gearbox on gear ratio

Regarding the efficiency (Figure 7), the conventional gearboxes are the most favourable, while planetary and cycloidal have very similar values (somewhat lower compared to conventional ones). The efficiency of the harmonic reducers is considerably lower in relation to all other types of gearboxes, and for gear ratios greater than 1:120 it records a drastic drop, which limits its application in this range.

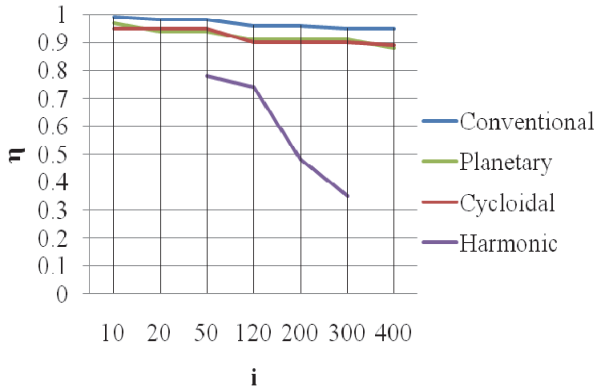

Fig.7. Dependence of the efficiency of the gearbox on gear ratio

Figure 8 shows the dependence of the length of the gearbox on gear ratio. Conventional gearboxes have the largest length, and the harmonic have the smallest. The highest height (Figure 9) has conventional reducers again, while planetary and harmonic are in similar housings. Cycloidal reducers have a slightly higher value of this dimension, since it mostly depends on their external diameter, and it is known that the external diameter of the cycloidal reducer represents its largest dimension.

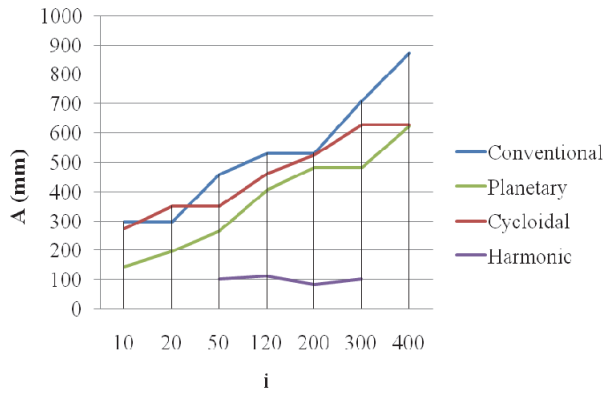

Fig.8. Dependence of the lenght of the gearbox on gear ratio

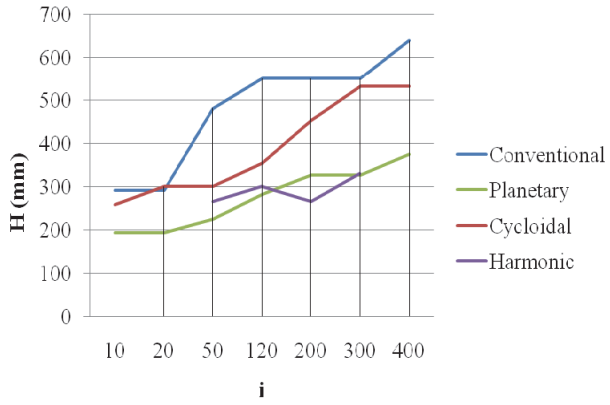

Fig.9. Dependence of the height of the gearbox on gear ratio

5. CONCLUSIONS

Gearboxes with high gear ratios are increasingly required in modern industrial practice (robotics, satellites, renewable energy systems, modern numerical processing centres, military industries, ...). First of all, they are expected to work reliably in high gear ratios, while the dimensions, mass, efficiency and price remain in real and acceptable frameworks.

Until a few decades ago, conventional gearboxes were used for this purpose. Today, more and more modern types of modern gearboxes are used (planetary gearboxes, harmonic gearboxes, cycloidal gearboxes, etc.).

In this paper, a comparison of the basic operating characteristics of conventional, planetary, cycloidal reducers and harmonic drives is carried out in the function of a gear ratio. The catalogues of these types of reducers of world-renowned manufacturers are used.

Based on the analysis, the following conclusions can be made:

- The highest efficiency has conventional gearboxes regardless of the size of the gear ratio;
- Planetary and cycloidal reducers also have a very high and acceptable value of the efficiency in the entire analysed range of gear ratios;
- The efficiency of the harmonic gearboxes for gear ratios greater than 1:120 records a drastic decrease and this limits their use;
- Conventional gearboxes have the biggest mass and harmonic have the smallest;
- When it comes to dimensions, the harmonic reducers are the most favourable, and then the planetary reducers are the most suitable;
- In the case of a cycloidal reducers, it is necessary to work on obtaining even more compact construction, while in the harmonic exploration researches, they should be directed towards obtaining a higher efficiency and extending the range of possible gear ratios;
- Conventional gearboxes, regardless of the lowest cost and high efficiency, are not an acceptable solution when the main criteria for choosing are mass and dimensions;
- Taking into consideration all the analysed parameters, planetary gearboxes continue to present the best solution when it comes to high gear ratios.

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