CHARACTERISTICS AND OVERVIEW OF KNOWLEDGE OF CURRENT RESEARCH IN THE PRODUCTION OF HARMONIC GEARBOX

DANIELA KEPEN HARACHOVA

Technical University of Kosice, Faculty of Mechanical Engineering, Department of Structural and Transportation Engineering, Kosice, Slovak Republic

DOI: 10.17973/MMSJ.2023_10_2023023

daniela.kepen.harachova@tuke.sk

The range of applications for drives and gears stretches over numerous technological fields. The gearbox is found in every mechanical machine and represents only one small but important sub-application. Industry as a whole has a constant demand for new individual solutions tailored to solve particular problems. But again and again, it is called upon to find new ways of transmitting movements that a particular component is required to conduct so as to attain a particular result. Harmonic drive products are unique precision speed reducers playing important roles in robots, semiconductor manufacturing systems, factory automation equipment and furthermore, in aerospace equipment. The greatest benefits are the zero-backlash characteristics and the weight and space savings compared to other gears because our gear mechanism consists of only three basic parts. They are the: Wave Generator, Flexspline and Circular Spline.

KEYWORDS

Harmonic drive, flexible wheel, zero backlash, insertion the teeth, transfer effectiveness.

1 INTRODUCTION

The Harmonic drive principle was patented in 1955 by the American Walter Musser. Figure 1 shows a sketch of a harmonic gear, as probably Mr. Musser prepared it. Later in 1970, USM Corporation and Hasegawa Gear Works establish two new plants, Harmonic Drive System GmbH in Germany and Harmonic Drive Systems Inc. in Japan, with the intention of expanding the production of harmonic gears in the industrial market worldwide. Market demands forced the company to constantly develop and expand the range of different types and sizes of these precision gearboxes. This product is primarily used in industrial robots, machining and printing machines.

The European aviation industry started using harmonic gears in 1976, mainly because of the high precision and low weight of these gears.

In 2006, the company Harmonic Drive LLC was established, consisting of the original HD Systems, Inc. and Harmonic Drive Technologies, Nabtesco, Inc., becoming a worldwide distributor and service center for harmonic transmissions.

The harmonic drive is a type of gear [Malakova 2021, Nikitin 2022] arrangement often referred to as a strain wave gear because of the way it works. It is a kind of reduction gear mechanism consisting of a minimum of three main components. These components interact in a way that allows for very high precision reduction ratios that would otherwise require much more complex and voluminous mechanisms.

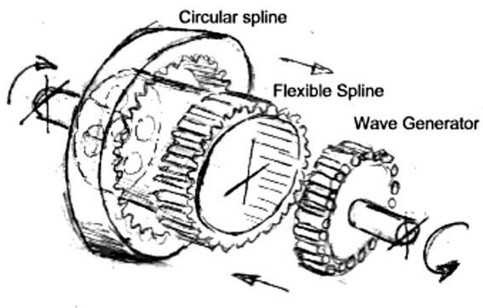


Figure 1. Sketch of Harmonic gearbox

The first peculiarity consists in the fact that a greater number of teeth simultaneously participate in the engagement and thus the transmission. The greater the of load will transmit flexible member team will grow and its deformation and therefore a greater number of teeth will huddle in toothed.

The second peculiarity the harmonic gearing [Harmonic Drive 2005, Ianici 2019] rests in that, due to changes in shape of the elastic wheel from the load, or due to the choices an shape of the wave generator there is a change a very the small the relative movement between the teeth, the contained the with in toothed engagement.

The third particularity is also conditional on the design of the flexible wheel rests reduce of angles of pressure of kinematic pair of wave generator - of the flexible wheel, as reflected by the reduce friction of sides this pair in compared catch cam - satellite in the planet gear.

2 DESCRIPTION OF THE HARMONIC GEARBOX

The harmonic gear transmission (Fig. 2) [Harmonic Drive 2005] is designed as a floating two-wave cam wave generator. It consists of three main components:

- Wave Generator
- Flexspline
- Circular Spline

A flexible wheel has external gearing, a rigid wheel has internal gearing [Ianici 2019]. Both wheels have the same module and pitch. The flex spline has fewer teeth than solid wheel. The wave generator is elliptical in shape and acts as a link with two rollers that rotates within the flexspline, causing it to mesh with the circular spline progressively at diametrically opposite points.

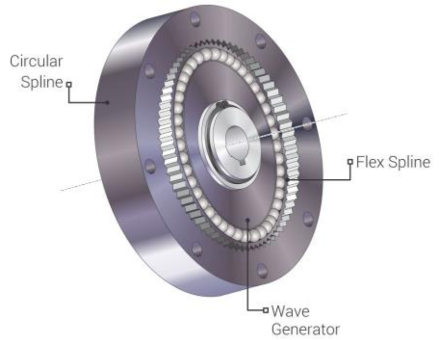


Figure 2. Harmonic gearbox

2.1 *Wave Generator*

The wave generator has an elliptical shape and is encircled by an elliptical ball bearing. As the shaft rotates, the edges change position, so it looks like it is generating a motion wave. This part is inserted inside a flexspline that is made out of a torsionally stiff yet flexible material. The material takes up this wavy motion by flexing according to the rotation of the input shaft and also creates an elliptical shape. The Wave Generator is typically used as the input, usually attached to a servo motor.

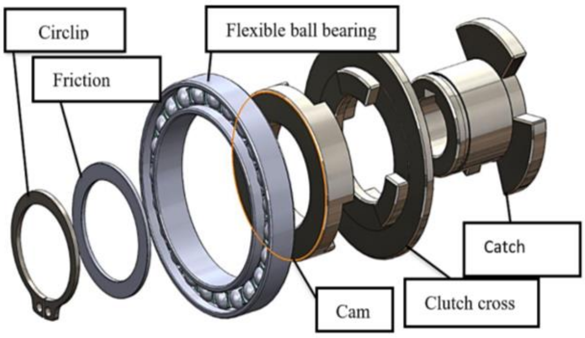


Figure 3. Wave generator assembly

The cam, which has a specially modified shape, is connected to the driven follower by means of an Oldham clutch. This method of mounting with the use of a clutch will allow relative movement between the cam and the follower.

2.2 *Flexspline*

The outer edge of this flexspline features gear teeth [Malakova 2021] that are suitable for transferring high loads without any problem. To transfer these loads, the flexspline is fitted inside the circular spline which is a round gear featuring internal teeth. This outer ring is rigid, and its internal diameter is marginally larger than the major axis of the ellipse formed by the flexspline. This means that the circular spline does not assume the elliptical shape of the other two components, but instead, it simply meshes its inner teeth with those of the outer flexspline side, resulting in the rotation of the flex spline.
The shape the flexspline depends on the type of wave generator that is inserted during assembly into the open part of the flexspline [Ianici 2019]. Figure 4 shows of the flexspline assembly also with the gearbox output element mounted.
Holes are drilled through the closed part of the cylindrical container. With the help of screws guided through these holes, the output member of the gear is subsequently mounted, to which the loads can be connected in the necessary manner.

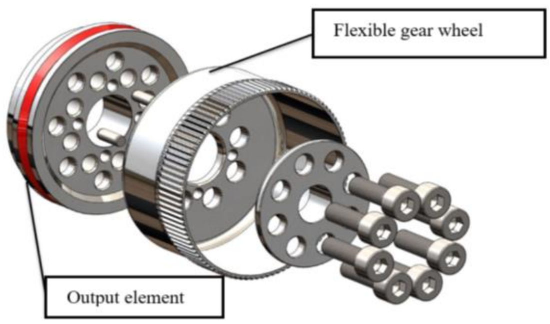


Figure 4. Flex spline assembly

2.3 *Circular Spline*

The Circular Spline (Fig. 5) is a rigid ring with internal teeth. When the gear is assembled it engages the teeth of the Flexspline across the major axis of the Wave Generator ellipse. This engagement is like an ellipse inscribed concentrically within a circle. Mathematically, an inscribed ellipse will contact a circle at two points.
However, the gear [Malakova 2021] teeth have a finite height. So, there are actually two regions (instead of two points) of tooth engagement. The Circular Spline has two more teeth than the flex spline and is fixed to the gear housing.

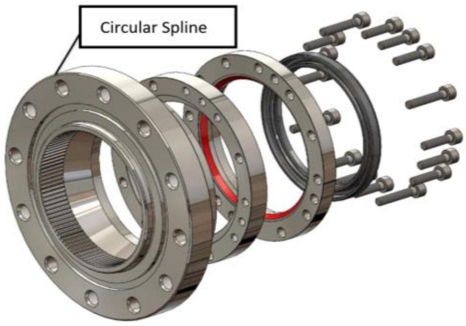


Figure 5. Assembly drawing of a rigid gear wheel

3 GEARING IN HARMONIC GEARBOXES

From the beginning, gearing with trapezoidal teeth was used for harmonic gearboxes. These gearboxes had 15-20% teeth in engagement, which made it possible to transmit a relatively high torque. However, there was wear on the teeth, especially their tips, and as a result, accuracy and repeatability decreased.

Figure 6. Original gears of harmonic gearboxes

Harmonic Drive developed a unique gear tooth profile that optimizes the gear tooth engagement. It has a special curved surface unique to the S tooth profile that allows continuous contact with the tooth [Harachova 2018] profile. It also alleviates the concentration of stress by widening the width of the tooth groove against the gear tooth thickness and enlarging the radius on the bottom. This tooth profile enables up to 30% of the total number of teeth to simultaneously. Additionally, the large tooth root radius increases the tooth strength compared with an involute tooth. This technological innovation results in high torque, high torsional stiffness, long life and smooth rotation.

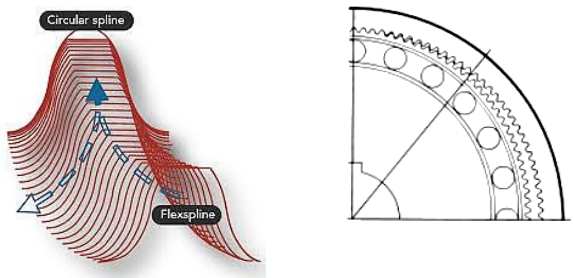


Figure 7. Unique gear tooth profile

4 THE WORKING PRINCIPLE OF HARMONIC DRIVE

1. The Flex spline is slightly smaller in diameter than the Circular Spline and usually has two fewer teeth than the Circular Spline. The elliptical shape of the Wave Generator causes the teeth of the Flex spline to engage the Circular Spline at two opposite regions across the major axis of the ellipse (Fig. 8) .

2. As the Wave Generator rotates the teeth of the Flexspline engage with the Circular Spline at the major axis (Fig. 8).

3. For every 180-degree clockwise movement of the Wave Generator, the flexspline rotates counterclockwise by one tooth in relation to the Circular Spline (Fig. 8).

4. Each complete clockwise rotation of the Wave Generator results in the flexspline [Ianici 2019] moving counterclockwise by two teeth from its original position, relative to the Circular Spline. Normally, this motion is taken out as output (Fig. 8).

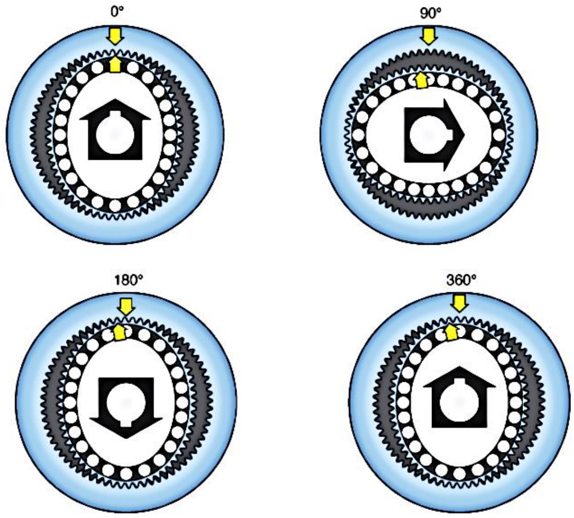
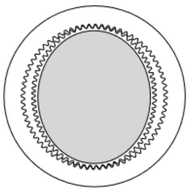


Figure 8. The workings of harmonic drive

When assembling the wave generator, care must be taken to ensure that the engagement of the teeth is evenly distributed on both sides of the major axis of the ellipse (Fig. 9).



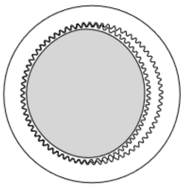


Figure 9. Correct assembly **Figure 10.** Incorrect assembly

Incorrect assembly is manifested by increased input torque and uneven, noisy operation of the gearbox (Fig. 10).

5 CHARACTERISTICS OF THE HARMONIC GEARBOX

Harmonic gearboxes are characterized by the possibility of a high gear ratio. In one stage, it is possible to achieve a gear ratio of up to 160 with the components of harmonic gearboxes, while these gearboxes are smaller and lighter than classic gearboxes mechanisms.

Characteristics:

a) superior efficiency

The mating portion of each tooth is subjected to very little slide motion. Therefore, motion loss due to friction is reduced in spite of high reduction ratios, and the Harmonic Drive maintains a high level of efficiency which enables driving motors to be made smaller.

The main factors affecting effectiveness include:

- transmission load
- amount and viscosity of the lubricant used
- input speed

Higher efficiency is achieved at lower revolutions, lower oil viscosity and higher transfers. If these conditions are met, the efficiency can be up to 90%.

b) high-speed reduction ratio

A Harmonic Drive [Harmonic Drive 1995] has high single-stage coaxial reduction ratios of 1/30 to 1/320. This is why the Harmonic Drive provides high efficiency gearing without using complex mechanisms and structures.

c) high accuracy

With the Harmonic Drive, high positional and rotational accuracy are assured because a good percentage of its teeth are meshed at all times and are engaged at two zones 180 degrees apart. This means influences of tooth pitch errors and accumulated pitch errors on rotational accuracy are neutralized to assure high positional and rotational accuracy.

d) small number of components and ease of assembly

High reduction ratios can be achieved with only three gear components, and since all three components are co-axially aligned, the Harmonic Drive can be easily built into component-assembled products, allowing for simple configurations.

e) high torque capacity

The flexspline [Ianici 2019, Krajnak 2021] is made of special steel with a higher resistance to fatigue. Different from a typical power transmission device, each tooth is subjected to a negligible amount of force yet provides a high torque capacity because of the way the teeth come into contact with each other and because roughly 30% of the teeth in the flexspline are engaged at all times.

f) quiet operation

With the Harmonic Drive, quiet, minimal vibration operation is possible because the circumferential velocity of its teeth in mesh is low and the teeth provide a well-balanced force.

g) small-sized and lightweight

While being less than 1/3 the size of conventional gearing mechanisms in terms of capacity and less than 1/2 the weight, the Harmonic Drive provides the same levels of torque and speed reduction ratios as its conventional counterparts enabling machinery and equipment to be made smaller and lighter.

5.1 Torsional Stiffness

The principle of operation of Harmonic Drive is based on the mechanism of rotationally elliptical deformation of the flexspline using an elliptical wave generator and subsequent rolling of the gearing. However, this mechanism hides two sources of nonlinear behavior of harmonic transmission:

- gear stiffness
- backlash.

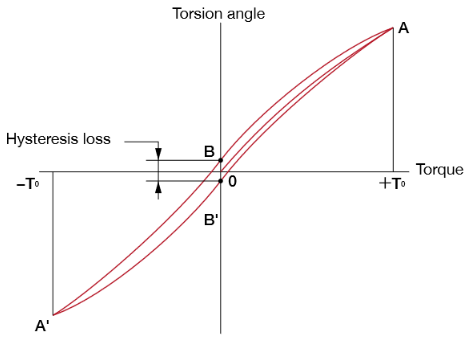


Figure 11. Torque - torsion angle diagram

Fixing the input side (wave generator) and applying torque to the output side (flexspline) generates torsion almost proportional to the torque on the output side. Figure 11 shows the torsional angle at the output side when the torque applied on the output side starts from zero, increases up to +T0 and decreases down to –T 0. As shown in Figure 088-1, when the applied torque is increased to the rated torque and is brought back to [zero], the torsional angle does not return exactly back to the zero point This small difference (B – B') is called hysteresis loss [Reducer Catalog 2021].

By increasing the magnitude of the torque when the Harmonic Drive input element is braked, more and more teeth come into engagement and thus the torsional stiffness increases, since more teeth participate in the transmission of the torque at the same time.

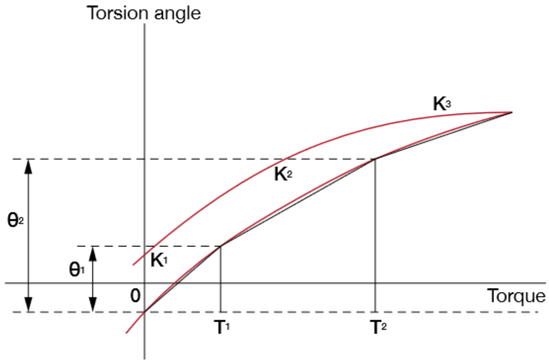


Figure 12. Spring constant diagram

As shown in Figure 12, this "Torque – torsional angle diagram" is divided into 3 regions, and the spring constants in the area are represented by K 1, K2 and K3 [Reducer Catalog 2021].

5.2 *Backlash-free (lost motion)*

Backlash [Chen 2014, Tang 2020] (Fig. 13) is defined as excess play between the rolling teeth. Compared to the ideal case of rolling an involute profile, when we consider an ideal state without will. In practice, backlash is achieved by adjusting the gear profile or by changing the axial distance between a pair of gears. The maximum dead run value for harmonic gears is v max = 8.7*10-4, i.e. 3 arc minutes. It follows from this that harmonic transmissions are very accurate, which is also one of their advantages.

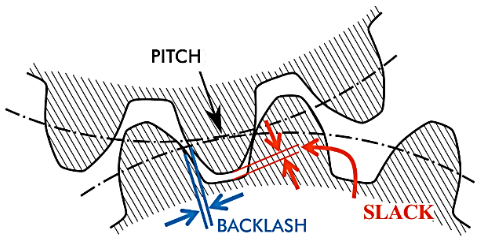


Figure 13. Backlash and slack in a gear system

Through analysis of transmission principle, the backlash of harmonic drive transmission could be decomposed into two dominant components including lost motion caused by clearance and lost motion caused by elastic deformation. The source of clearance mainly includes tooth clearance between circular spline and flexspline, the clearance from Oldham coupling in the wave generator, while the elastic deformation is mainly due to flexspline under load of torque.

The dead run interpretation is a nonlinear function that includes both the dead run effect and the torsional characteristic of teeth in engagement with a changing loading torque. This curve approximates the real characteristic. We will describe this function as follows:

$$f\,(\delta) = \begin{cases} \delta - b_{s'} & \delta > b_s \\ 0, & \\ \delta + b_{s'} & \delta > b_s \end{cases} \qquad (1)$$

This description divides the characteristic into three zones, since we are also considering the reverse operation of gear wheels. The size of the dead zone in this case is equal to the size of 2b. Figure 14 is a representation of these three zones.

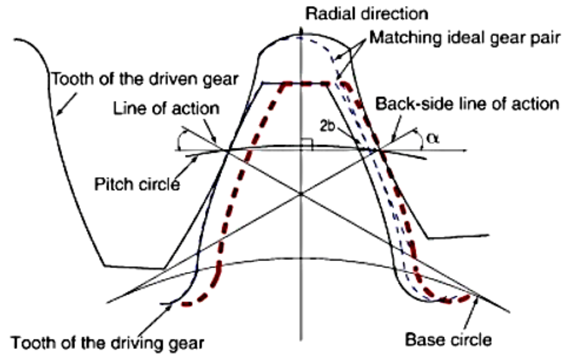


Figure 14. Minimum clearance between the teeth

6 BASIC TYPES OF HARMONIC DRIVE GEARS

When choosing a suitable harmonic drive, it is necessary to take into account the needs of the customer, as well as the real possibilities of all parts of the device into which we place the harmonic reducer (Fig. 15). The development focused on accuracy, efficiency, increasing the transmitted torque and the lifetime of the components.

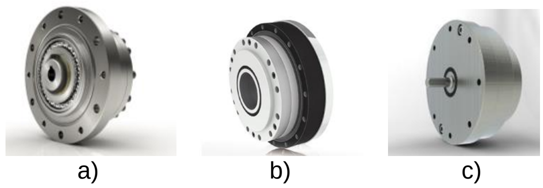


Figure 15. Harmonic gearboxes: a) CSF, b) SHF, C) SHG

Among the aforementioned gearboxes, we must mention the subsidiary (Micromotion) Harmonic Drive, which specializes in the production of high-precision micro drives (Fig. 16) with a focus on precision and compact dimensions. Harmonic Drive [Lightweight Harmonic Drive 2010] miniature reducers offer zero backlash and high torque in a small package. With outline dimensions starting at just under 13 mm, these gears are commonly used in robotics and semiconductor devices. Miniature gearboxes are also available with precisely matched motors and encoders. Complete mini and supermini drives are available in 3 ratios and multiple configurations.

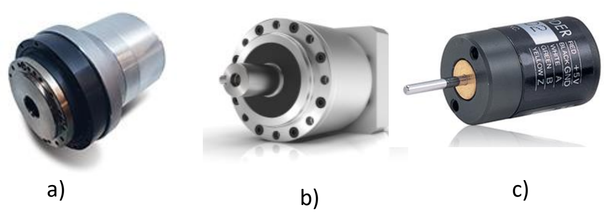


Figure 16. Micro-drives Harmonic gearboxes: a) SHA, b) HPN-L (planetary gearbox), C) Micro Encode HPN

Now let's look at the types of individual harmonic drive (Fig. 17).

Component Gear Sets - consisting of three basic components: flexspline, circular spline and wave generator; component gear sets offer ultimate design flexibility and can be tightly integrated in equipment sub-structures.

Gear Unit - housed component gearing combined with precision cross roller output bearing & flange. Very compact, robust and easy to use gearhead solution.

Simplicity Gear Unit - non-housed component gearing combined with a precision cross roller output bearing. Similar as well as previous Gear Units, without the housing and output flange, for tighter integration into the customer's housing or machine structure.

Another product is Harmonic Planetary Gears, which have lower gear ratios, usually working at higher speeds where very high precision is often required. The flexible construction of the gear in the output stage means that we guarantee constant high precision throughout its lifetime - we call it Permanent Precision. Products: HPN, HPGP, HPG.

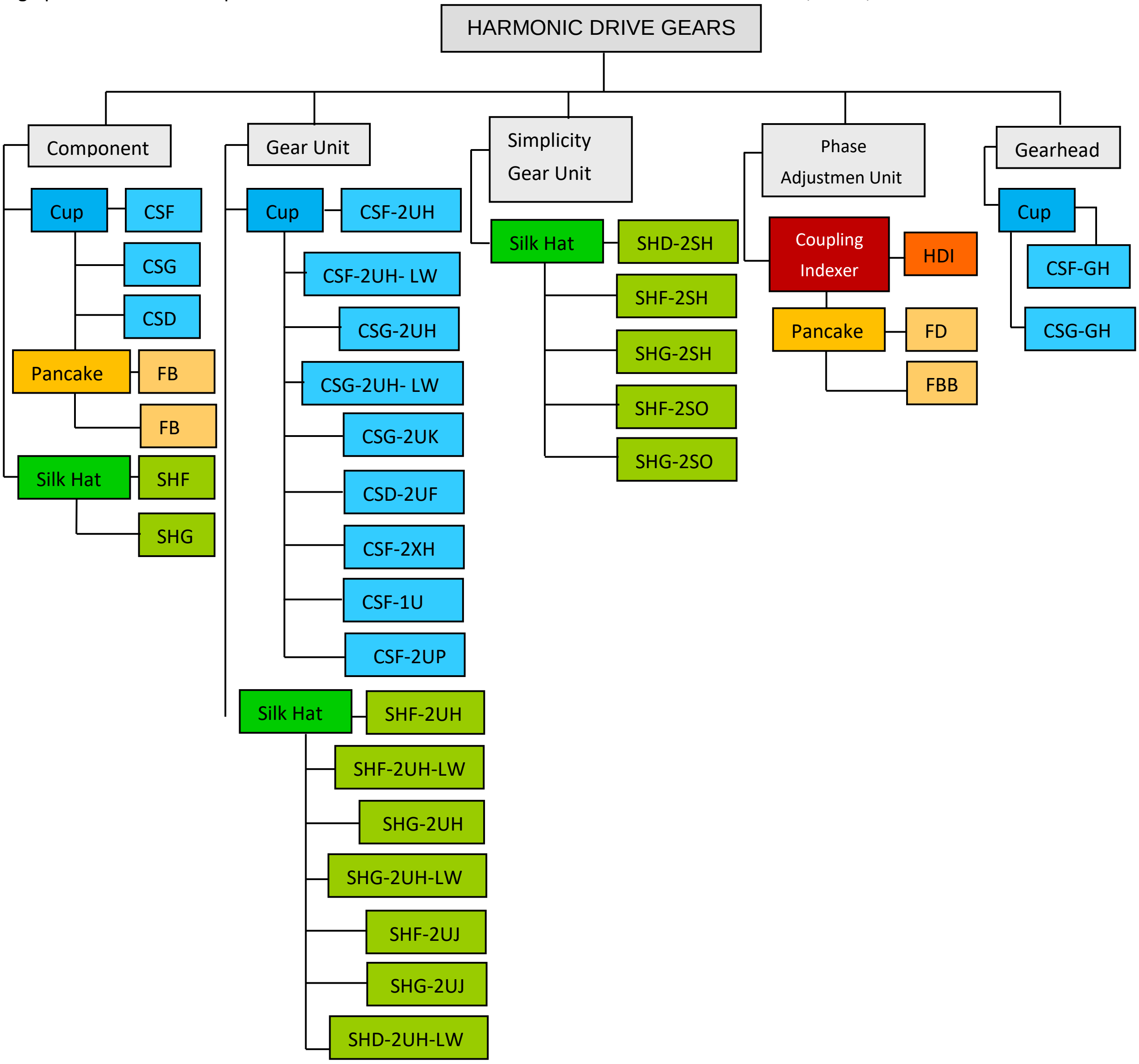


Figure 17. Basic types of harmonic gearboxes

Harmonic Drive servo products are highly desirable, being the perfect combination of highly dynamic compact servo motors, precision Harmonic Drive gear component kits, and integrated output bearings with high load capacity and tilt resistance. Hollow shaft servo drive products: IHD, BHA, CanisDrive. AlopexDrive, FHA-C Mini, YukonDrive. Servo drives with solid shaft: LynxDrive, FLA, FHA-C Mini MZE, YukonDrive.

7 HARMONIC GEARBOXES IN PRACTICE

Harmonic Drive® transmissions and drives are used in a wide variety of applications, each utilizing a different characteristic of transmission technology. Some applications depend on zero backlash [Tang 2020] and high position accuracy. Some require a high torque-to-weight ratio. Others depend on the unique configurations available. Some installations use all of these attributes. Industrial robotics (Fig. 18 a)) is one of the main areas of application of Harmonic Drive gearbox components. These applications require zero backlash gears with high torque capacity, high torsional stiffness and excellent repeatability. The hollow shaft design is also popular as it allows for simple, elegant and reliable cable routing. Gears with large capacity crossed roller bearings are sometimes selected due to their compact form and are particularly suitable for use in a robot axis that places significant tilting moments on the joint output bearing.

Advances in medical equipment have continuously increased the demands for highly accurate motion control [Krenicky 2022, Trojanova 2021]. Today, harmonic gears and planetary gears are widely used in numerous medical devices, including surgical tables, medical diagnostics, and a wide range of gear pumps for medical administration applications. Only in this way, can thea patient beds be perfected adjusted. Moreover, surgical tables are also needed to be equipped with a gear motor that are featured with the characteristics of low voltage and safe, and medical diagnostics need to use the hollow shaft gearbox for power scanning. For instance, devices like MRI & CAT scanning machine all need to employ a retransmission ring to rotate. In order to achieve smooth and quiet surgeries, an effective right-angled planetary gearbox is definitely a must. An example of this is the transmission units used in the rotation axes of a stereotactic manipulator used for brain surgery (Fig. 18 b)). The manipulator is a six-axis robotic arm that supports the operating microscope used by the surgeon. As the operation progresses, the microscope overlays computer data on the current view of the operative field, acting as a head-up display to accompany the surgeon during the operation. The accuracy and reliability of the Harmonic Drive [Harmonic Drive 2005] are critical to successful surgical procedures.

Aviation engine and aerospace gearboxes are extremely high applications that require extremely high reliability and tightness tolerances. Aerospace gearboxes are used in aircraft and engine power transmission. The main reducer, intermediate reducer and tail reducer in the helicopter transmission system are used for the power transmission of the aircraft, and the propeller engine reducer and the reducer in the turboshaft engine body are mainly used for the engine power transmission. In addition, it is used as auxiliary transmission for various types of engines and aircraft accessory transmissions.

a) b)

Figure 18. a) industrial robot, b) robotic surgical systems in brain tumor operations

8 CONCLUSIONS

The advanced mechatronic systems of today's positioning mechanisms have increasingly high demands on the accuracy of translational and rotational movements. Part of the mechatronic system is also the control unit controlling the given drive system. Harmonic gearboxes are widely used due to the specific and unique properties resulting from their mechanism. This mechanism is based on the rolling of the toothing caused by the elliptical deformation of the elastic gear wheel. It has excellent properties especially in a steady state at constant speeds and under suitable ambient conditions. Outside the steady state, these mechanisms show a highly non-linear characteristic, and the kinematic error of the transmission is prominent. These characteristics are caused by various factors, primarily due to the design of the transmission.

The non-linear torsional stiffness of the transmission mechanism causes problems for the control and regulation of the drive system. This issue is relevant in many areas of harmonic transmission application, especially in applications with a priority on accuracy positioning.

ACKNOWLEDGMENTS

The contribution was prepared within the solution of grant projects: VEGA 1/0528/20 - Solution of new elements for mechanical system tuning.

KEGA 029TUKE-4/2021 - Implementation of modern educational approaches in the construction of transmission mechanisms.

REFERENCES

[Chen 2014] Chen, X., et al. The parametric design of double-circular-arc tooth profile and its influence on the functional backlash of harmonic drive. Mech. Mach. Theory, 2014, Vol. 73, pp. 1-24.

[Harachova 2018] Harachova, D., et al. Insertion of teeth into engagement and their effect the deformation of the elastic wheel in harmonic gear. Ad Alta, 2018, Vol. 8, No. 1, pp. 265-267. ISSN 1804-7890.

[Harmonic Drive 1995] Harmonic Drive Technologies, Peabody, MA, HDC Cup Component Gear Set Selection Guide, 1995.

[Harmonic Drive 2005] Harmonic Gear Strain Wave Gear. Available at: https://harmonicdrive.de/en/technology/harmonic-drive-strain-wave-gears

[Ianici 2019] Iancil, S., et al. Contributions to determining the trajectory of a point on the average fiber of the flexible wheel of a double harmonic transmission. Analele Universitatii 'Eftimie Murgu', 2019, Vol. 26, No. 1, pp. 99-106. ISSN 1453-7397.

[Krajnak 2022] Krajnak, J., et. al. The failures of flexible couplings due to self-heating by torsional vibrations – validation on the heat generation in pneumatic flexible tuner of torsional vibrations. Engineering Failure Analysis, 2022, Vol. 119, pp. 1-13, ISSN 1350-6307.

[Krenicky 2022] Krenicky, T., Nikitin, Y., Bozek, P. Model-Based Design of Induction Motor Control System in MATLAB. Appl. Sci., 2022, Vol. 12, 11957.

[Lightweight Harmonic Drive 2010] Lightweight Harmonic Drive® Gears and Actuators Help Improve the Productivity of Factory Automation Systems. Available at: www.harmonicdrive.net.

[Malakova 2021] Malakova, S., et al. Influence of the shape of gear wheel bodies in marine engines on the gearing deformation and meshing stiffness. J. of Marine Science and Engineering, 2021, Vol. 9, No. 10, pp. 1-22. http://dx.doi.org/10.3390/jmse9101060.

[Monkova 2019] Monkova, K., et al. Effect of the Weight reduction of a Gear Wheel on Modal Characteristics. MATEC Web Conf., 2019, Vol. 299, pp. 1-6.

[Nikitin 2022] Nikitin Y., et al. Vibration diagnostics of spiroid gear. Manag. Systems in Production Engineering, 2022, Vol. 30, No. 1, pp. 69-73. ISSN 2450-578.

[Reducer Catalog 2021] Reducer Catalog - Harmonic Drive https://www.harmonicdrive.net/_hd/content/documents1/reducer_catalog.pdf

[Xiaoxia 2010] Xiaoxia Ch., et al. The investigation of elongation of the neutral line in harmonic drive. In: 2010 Int. Conf. on Computer Design and Applications, 2010, Vol. 4, pp. V4-383-V4-386.

[Tang 2020] Tang, J. Gear Basics: Backlash vs Lost Motion. Available at: https://blog.orientalmotor.com/gear-basics-backlash-vs-lost-motion

[Trojanova 2021] Trojanova, M., et al. Estimation of Grey-Box Dynamic Model of 2-DOF Pneumatic Actuator Robotic Arm Using Gravity Tests. Applied Sciences, 2021, Vol. 11, No. 10, Art. No. 4490.

CONTACTS:

Daniela Kepen Harachova, Ing. PhD.
Technical University of Kosice
Faculty of Mechanical Engineering
Department of Structural and Transportation
Letna 9, 04200 Kosice, Slovak Republic
daniela.harachova@tuke.sk