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Development of precision drive unit to be universally used as robot joints with high power density and modular construction at Wavedrive Kft.

[1]Balázs Göncfalvi, [1]Róbert Neumann, [2]Richárd Horváth, [1,3]Róbert Krisch

[1]*Wavedrive Kft. Törökbálint, Hungary, info@wavedrive.hu*
[2] Óbuda University, Bánki Donát Faculty of Mechanical and Safety Engineering. *Budapest, Hungary, horvath.richard@bgk.uni-obuda.hu*
[3]*Budapest University of Technology and Economics, Budapest, Hungary, krisch.robert@gt3.bme.hu*

Abstract

The main focus of this article is to present the unique and widely applicable precision drive systems developed by Wavedrive Kft., which are mainly a combination of an electric motor, strain wave gear elements, as well as encoders on the input and/or output side. This R&D project aims to develop more precise drive system solutions with minimal dimensions for the industry. The experimental drive systems were tested in industrial conditions to measure them in a real application example. Based on the test results, new precision drive units were designed and manufactured. Also, a unique, compact drive system was developed to meet the expectations of medium-load applications. The design- and manufacturing project was sponsored by the Ministry of Innovation and Technology under the tender number 2018-1.1.1-MKI-2018-00152.

Keywords: Innovative Precision Drive System; Strain Wave Gear; Finite Element Model

1. Introduction

Wavedrive Kft. (Previously known as K.K.K. 99 Kft. until 2022. September) has received a grant in the 2018-1.1.1-MKI-2018-00152 tender for research and development of high-recision drive units that can be used in high-accuracy robotic applications. Precision drives are widely used in healthcare systems, industrial manipulators, manufacturing and measurement devices.

As part of the main research and development project at Wavedrive Kft., we constructed and evaluated several drive configurations, which are a combination of different strain wave drive units, Brushless Direct Current (also known as BLDC) motors, and encoders on the input and/or output side. This article deals with the development of all the different combinations possibilities of potential drive units as well as their tests and results.

1.1 The Operating Principle of Strain Wave Drives

Strain wave drives are high reduction ratio, backlash-free, high power density precision drives. The very high reduction ratio requires the combination of the main elements shown in Figure 1. To achieve this high ratio and power transmission, the input wave generator’s lobes deform the flexible bearing, which deforms the wave gear into the teeth of the rigid gear, thus initiating the connection to turn the flexible gear. The main elements are arranged coaxially in both the flat and cylindrical construction.

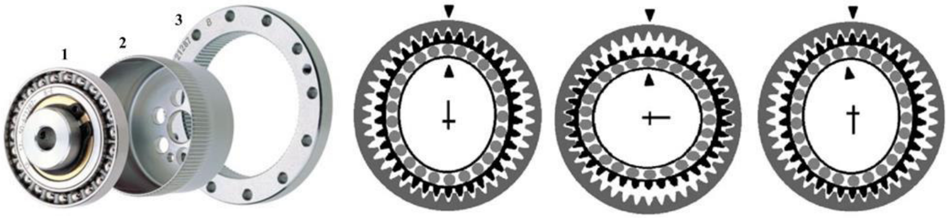

Figure 1. Cylindrical strain wave drive unit's main elements and working principle flexible bearing and wave generator (1), wave gear (2), rigid gear (3) [1].

The two main elements have a matching tooth profile, but the number of teeth on the wave gear is reduced by the number of lobe surfaces of the wave generator. Shown in Figure 2. is the operating principle of the cylindrical strain wave drive. This Figure it is shown how the periodic deformation travels around and distorts the flexible gear into the rigid gear, thus creating relative rotation. Strain wave drive units – in contrary to cyclo drives – are dynamically balanced, so they can be operated at a much higher input speed.

Regarding construction, there are two main types of strain wave drives: flat- and cylindrical wheel types. The flat wheel strain wave drives have a similar operating principle, but their design is partially different. In their case, the lobes of the wave generator, as well as the teeth of the wave- and rigid gears are formed on the face surface of a disc rather than on a cylindrical surface.

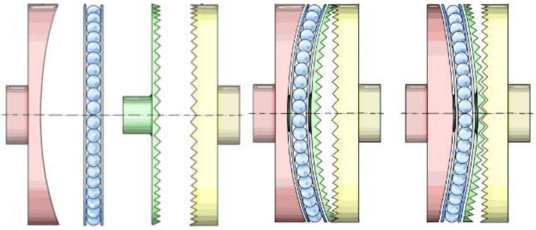

Figure 2. Illustration of the flat wheel strain wave drive's main elements [4]. From left to right: wave generator, flexible radial bearing, wave and rigid gear

The two main types of drives each have their advantages and disadvantages. The flat wheel drives typically have higher torsional stiffness but are less efficient in low-load cases. Meanwhile, the cylindrical construction is less optimal regarding torsion hence the more flexible design of the wave gear, but they can be operated with better efficiency. The reason for this is that the continuous periodic deformation of the cup-shaped wave gear requires less energy investment from the BLDC motor side. The outside dimensions of the different types are also different, so the installation environment has to be taken into account when selecting the appropriate drive system.

1.2 Development Guidelines

During this tender project, the four strain wave gear unit shown in Figure 4. were manufactured. Two flat- and two cylindrical wheel versions were built. Both two types can be assembled with or without an integrated brake. The prototypes have a modular design, so multiple parameters can be tested by replacing the interchangeable elements. In previous publications of this research and development project [5]., the experiences and test results of the drive systems were presented, which served as a reference during the development of the upgraded drive systems.

Figure 3. Prototypes of modular flat- and cylindrical wheel strain wave drive systems

In the case of the further developed versions, instead of a modular structure, the size and operation optimization were prioritized. The process consisted of several iterative steps, during which new cylindrical-type drive system prototypes were manufactured and assembled. These versions were operating in a similar power range as the ones from the first phase, but their enclosure size was much more compact. The dimensions of the experimental drive systems manufactured in the first phase of this R&D project are as follows: The outside diameter for the flat wheel strain wave drive system is 150 mm, minimum length is 84,8 mm, whereas the same parameters for the cylindrical wheel strain wave drive is 125 mm in diameter and 171,6 mm in minimum length. Depending on the type of the drive system, an output torque of 60-80 Nm can be measured on the output shaft. The highest tested motor speed was 1500 rpm for the flat wheel type and 3000 rpm for the cylindrical type drive systems. The optimized version of the cylindrical strain wave drive system manufactured during the second phase of the R&D project is capable of delivering 40 Nm of torque at a similar output speed, and its size has been significantly reduced: Its length is 107,5 mm with an outside diameter of 88 mm. Also, a small drive system prototype was developed and manufactured in parallel, which will be presented in Chapter 1.3.

1.3 Development of a compact cylindrical type strain wave precision drive system

In the latest phase of the R&D project, a small precision drive system was developed, in which all elements – including the wave generator and the wave- and rigid gears – are manufactured by Wavedrive Kft. The motor with an outside diameter of only 43 mm is – like the previous models – in this case also BLDC type, and is capable of continuously delivering 0,128 Nm of torque with a power of 70 W. Our goal is to develop a gear unit that can be well matched to these parameters. The main elements fit well with a commercially available flexible radial bearing with a diameter of 32 mm.

With these geometrical conditions, a gear ratio of $i = 50\text{-}120$ can be achieved. From this range, we implemented a gear ratio of $i = 60$. Also, a unique tooth profile was designed for both of the main elements. This reduction ratio provides optimal tooth engagement and – with appropriate efficiency – meets the requirements to be installed as the end-effector of a manipulator. In order to ensure optimal contact conditions, meticulously designed tooth profiles, gear geometry, and precise manufacturing are required. For that, we had to simulate the exact deformed shape of the flexible elements.

It is important to mention that the stress generated in the contacting elements depends to a large extent on the geometry of the flexible gear. The primary goal of our finite element tests is to optimize the geometry of the wave gear so that the stress is minimized, thereby maximizing the service life of the drive system. The following figures clearly show that the highest tension typically appears at the base of the teeth and at the base of the flat face of the wave gear.

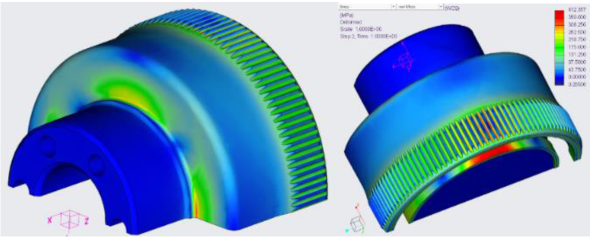

Figure 4. Stress distribution in the wave gear and flexible bearing (350 MPa < red color)

Aside from the tooth geometry, it is important to set optimal values for the length and wall thickness of the cup-shaped part. The dimensions of the flexible bearing determine the diameter of the cylindrical deformation zone. For this reason, efforts must be made to reduce the diameter of the hub, thereby increasing the area of the deformable surface. The optimization process with finite element tests is shown in Figure 5.

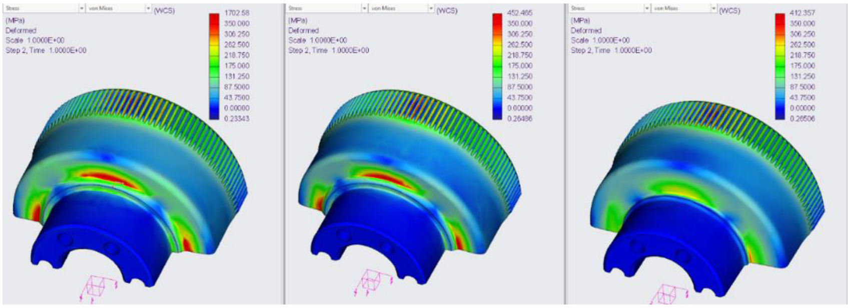

Figure 5. Optimization of wave gear geometry with finite element simulation

With the optimized geometry, the maximum stress at the base of the teeth is 364 MPa, and at the base of the cup-shaped part, only 283 MPa. The finite element simulation results also provide an opportunity to examine the deformed tooth profile, which served as input data for the calculation of the tooth geometry. The final tooth profile of the rigid and wave gears is the result of an iterative process, the aim of which is to ensure the best possible connection between the tooth pairs. By maximizing the contacting surfaces, it is possible to increase the efficiency of the gear unit, its service life, and the torque that can be transmitted by it. The final length of the complete drive unit equipped with a small BLDC motor is 44 mm, and its cross-section is 49x49 mm.

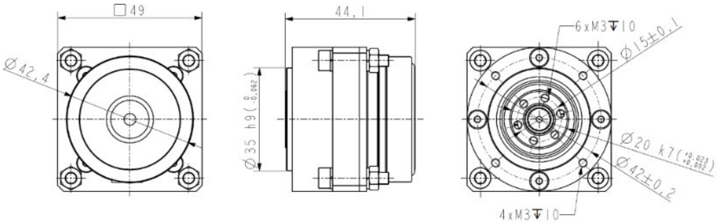

Figure 6. Front, side, and back view of Wavedrive's smallest precision drive unit

1.4 Testing Environment

During the R&D project, the compact drive system was tested on a continuously developed test bench. Providing the right test environment and measuring instruments is of high importance in order to obtain correct results that can also be compared with competing products.

The goal of the measurements is to validate the preliminary calculations and to carry out full lifecycle tests under a specified load. These tests are necessary to check the device for fatigue and whether the parts were made with appropriate production technology. In addition, it is also possible to measure the return accuracy, backlash, and torsional stiffness of the drive unit.

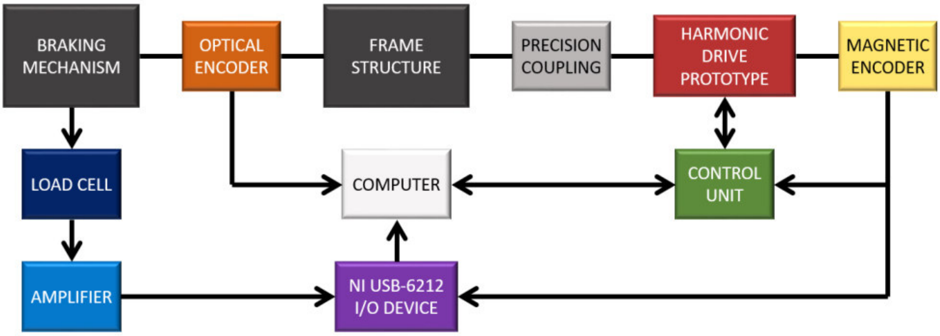

Figure 7. Block diagram of the testing environment setup

The base frame is made of steel hollow sections and sheet metal parts welded together, on top of which a cast bearing housing is mounted solidly. The drive system is mounted on one side of the shaft through a precision membrane coupling. The input rpm is monitored constantly with a magnetic encoder. On the output side, a high-resolution optical encoder is responsible for proper speeds and positioning. There is also a steel brake disc and a coaxially mounted steel bar attached to the output side of the shaft. The steel disc is braked through copper brake shoes mounted on a mechanism at the end of the bar. The copper shoes are adjustable to set the correct braking force. On the other side of the loading bar is a load cell so that the actual load can be continuously monitored. A signal amplifier is connected to the load cell; the signal is filtered by software. A multifunctional National Instruments USB-6212 data collector card transmits the signals of the load cell and the magnetic encoder on the input side to the evaluation computer.

Figure 8. Test bench for the precision drive units

1.5 Evaluation of the Results

Within the scope of this R&D project, six precision drive systems with significantly different parameters have been manufactured and assembled, including both cylindrical- and flat wheel type versions. The latest version of the developed drive systems is a very compact, cylindrical-wheel type unit, which fulfilled the pre-defined expectations, as the output torque did not drop under 5,62 Nm at 15 rpm and under constant load. The position recovery error remained below 0,001° in all measurement cases, and the backlash of the system was even smaller. The torsional stiffness of the drive system is 0,03 arcmin/Nm. Regarding these parameters, it can be stated that the developed compact drive system fully met the preliminary expectations and is suitable for implementation in any industrial environment requiring small size and high positioning accuracy.

2. Conclusion

Overall, the parameters of the drive systems developed by Wavedrive Kft. meet the requirements of industrial applications. Based on the results of tests and measurements, the performance and accuracy of the drive systems fit into other precision drive systems. Based on the experiences and conclusions gained during the project, our future plans include the installation of the prototype as an end-effector to the end of an industrial manipulator. This configuration is among further development possibilities of the experimental drive system. The next stage of this R&D project will be the comprehensive testing of a drive system of this type.

Acknowledgments

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