Tooth profile optimization for zero-backlash microgears

The novel P-toothing of the Micro Harmonic Drive® gear

Dr. Reinhard Degen, Dr. Rolf Slatter,
Micromotion GmbH
An der Fahrt 13
55124 Mainz, Germany
Telefone: +49 6131 669 27-0
Email: info@micromotion-gmbh.de

Abstract:

The Micro Harmonic Drive® gear is currently the world´s smallest zero-backlash gear system. Originally invented in 2001 by Micromotion GmbH this innovative gear design has successfully been transferred from a research environment into numerous industrial applications. The combination of high reduction ratio, excellent repeatability, high efficiency and high torque capacity offered by this gear principle make it highly suitable for precise positioning applications in semiconductor manufacturing equipment, medical devices, measuring equipment, optical devices as well as machine tools and even spacecraft.

This microgear, with an outer diameter of down to 6 mm and an axial length of only 1 mm in the smallest currently available size, provides gear ratios between 160 : 1 and 1000 : 1 in a single stage. These high ratios are necessary to convert the very high rotational speeds and very low output torques of micromotors into lower speeds and higher torques as required by real applications in industrial machines and equipment. The gear is manufactured by a special production process, called “Direct-LIG”, by which the individual gear components are formed galvanically in a 3-dimensional mould produced in a photoresist using X-ray lithography. This production process has been continually improved to allow the cost effective manufacture of microgears in small to medium series production.

The gear principle is based on the well-known Harmonic Drive® principle, used in the successful “macro-technologically” manufactured reduction gears of the same name. A major difference of the microgear is the use of a planetary gear to provide an initial speed reduction within the space envelope of the Harmonic Drive® gear stage. This planetary stage is provided with radially deformable planet gears, in order to avoid backlash in this reduction stage.

Until recently conventional gear profiles were applied to the Micro Harmonic Drive® gear – either involute profiles, or the IH profile, as invented for the "macro" Harmonic Drive® gear in the late 1980´s. These profiles have been optimised for production using conventional gear manufacturing techniques, such as hobbing, shaping and grinding. These techniques necessarily place limitations on the gear profiles that can be economically manufactured. The "Direct-Lig" process, on the other hand, allows more freedom for a true optimisation of the gear profile used. The use of X-ray lithography means that almost any 2-dimensional profile can be used to produce 3-dimensional gear teeth.

This paper will describe the development history of a unique new tooth profile, which is leading to a dramatic improvement in the performance characteristics of the Micro Harmonic Drive® gear. This new profile, which will be first shown to the public in early 2005, leads to a 200% increase in torque capacity and a 200% increase in torsional stiffness. This has the result that this zero-backlash gear system is now not only significantly more accurate than other microgears, but also offers a substantially higher power density and torsional stiffness. The paper will also show how this improved performance is extending the application area of this microgear even further.

1. From the Mini- to the Micro Harmonic Drive® gears

Micro gear systems represent a key element in micro drive systems. Only by using suitable micro gear systems it is possible to apply existing micro motors operating with speeds of up to 100.000 rpm at output torques in the range of some µNm [1] in a wide field of different applications. To access new innovative fields of application in the range of micro drive systems Micromotion GmbH has developed a new generation of high precision and zero backlash micro gear system: the Micro Harmonic Drive® (see Fig. 1).

Until recently the physical size of these drive components was much larger than that of both the components to be handled and the necessary workspace, with the result that many machines and robots for microassembly have dimensions far in excess of the necessary working area [2]. There is now a clear trend to equip physically smaller machines with micro drive systems. These machines have a smaller footprint and often higher assembly accuracy than the previous generation of machine.

Fig. 1: Micro Harmonic Drive® gearbox and actuator

2. The Micro Harmonic Drive®

Microgears are not a particularly recent development and micro-spur gears or micro-planetary gears have been available in the market for a number of years. However, these products suffer from poor positioning accuracy and are therefore rarely used for positioning applications in machines. These previous solutions either have backlash or only permit very light loads. What is needed are micro-gears that are not only very small in size, but also feature high repeatability, zero backlash, high reduction ratios and a low parts count. These requirements inspired the development of a new micro-gear, the Micro Harmonic Drive® gear [3] (Fig. 1).

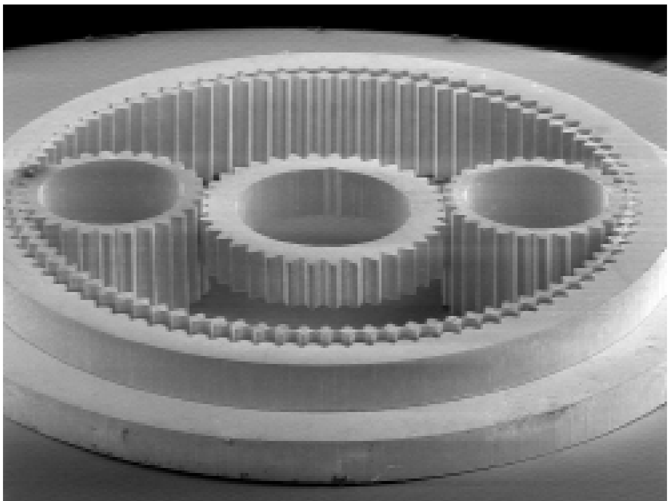


Fig. 2: Micro Harmonic Drive® gear component set

The Micro Harmonic Drive® gear component set has an outer diameter of just 6 or 8 mm and an axial length of 1 mm. Fig. 2 shows a REM picture of the component set. It can provide reduction ratios between 160:1 and 1000:1 in one stage. In order to allow easy integration in a wide range of different applications the component set is typically mounted inside a micro-gearbox of the MHD series with shafts mounted in pre-loaded ball bearings (see Fig. 3). The MHD gearboxes are available in two sizes with 8 mm or 10 mm outer diameter, either with an input shaft or for direct coupling to commonly available micro-motors from Arsape, Escap, Faulhaber, Maxon, Mymotors, Myonics, Phytron etc. [4]. A hollow shaft with an inner diameter of up to 1.5 mm passes along the central axis of rotation of the gearbox.

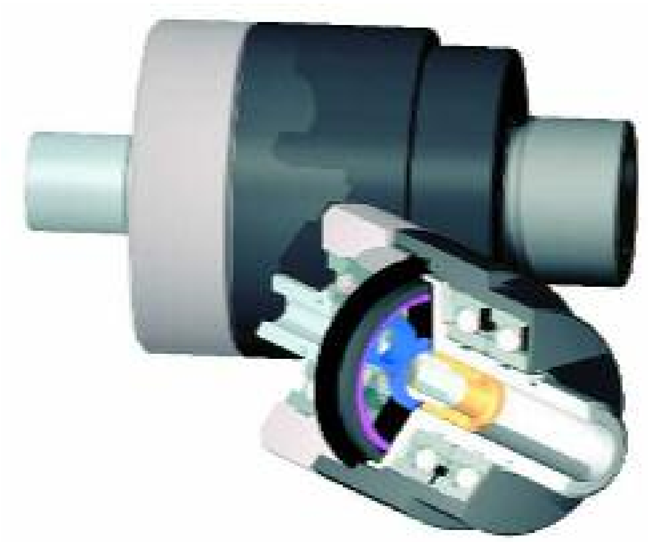


Fig. 3: Micro Harmonic Drive® MHD gearbox

3. Principle of operation

The principle of operation is similar to the conventional „macro-technological" Harmonic Drive® gear [3], with the difference that the Wave Generator consists of a planetary gear stage. This enables very large reduction ratios in a small envelope. This is necessary, because most currently available micromotors only produce adequate torque at very high output speeds, typically more than 50.000 rpm, and a high reduction ratio then helps provide sufficient torque at an acceptable speed for practical motion control applications.

The basic elements of the Micro Harmonic Drive® gear system are the Wave Generator consisting of two planetary wheels and a sun gear wheel and the three gear wheels Flexspline, Circular Spline and Dynamic Spline. The Wave Generator deflects the elastically deformable Flexspline elliptically across the major axis. Due to that the teeth of the Flexspline engage simultaneously with the two ring gears – Circular Spline and Dynamic Spline - in two zones at either end of the major elliptical axis (see Fig. 4). Across the minor axis of the elliptically deflected Flexspline there is no tooth engagement.

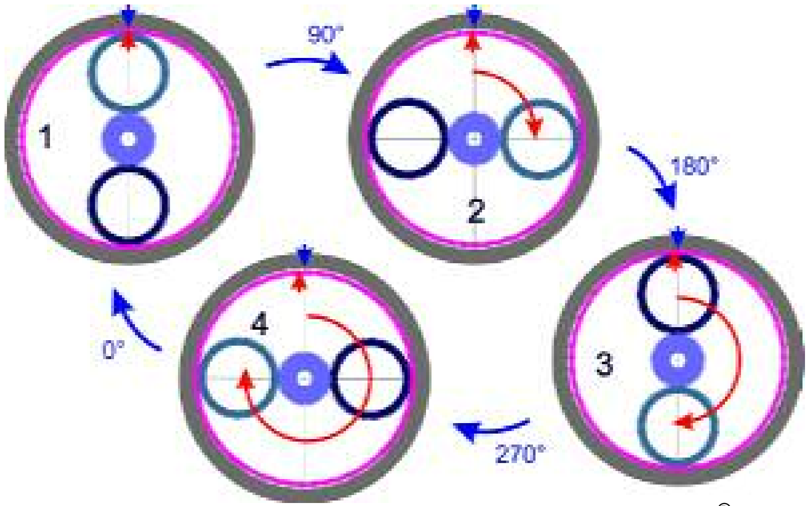


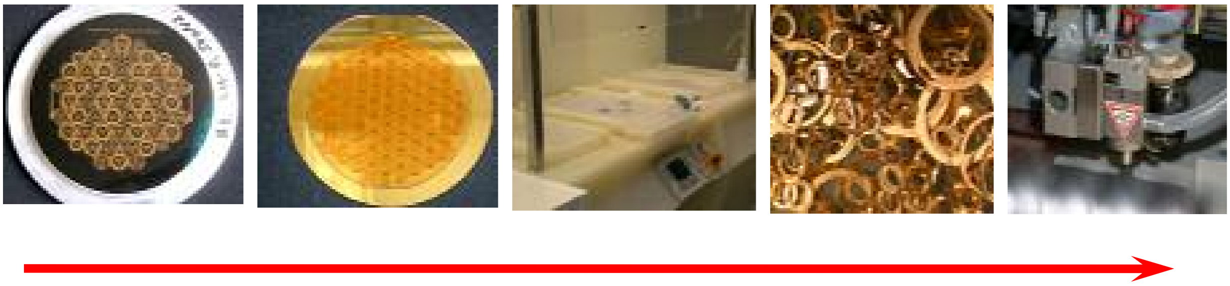
Fig. 4: Operating principle of the Micro Harmonic Drive® gear

When the sun wheel of the Wave Generator rotates, the zones of tooth engagement of the Flexspline travel with the angular position of the planet wheels of the Wave Generator. The difference of two teeth between the Flexspline and the Circular Spline results in a relative movement between these gear wheels. After a complete rotation of the planet wheels of the Wave Generator the Flexspline moves relative to the Circular Spline by an angle equivalent to two teeth. The Dynamic Spline is used in the flat type gear system as the output element and has the same number of teeth as the Flexspline and therefore the same rotational speed and direction of rotation.

The planet wheels have the primary task of realizing the exact deflection of the Flexspline. Additionally the planet wheels have to compensate errors of fabrication and wear of the gear system whilst still providing an exact deflection of the Flexspline. This error compensating property of the planet wheels is made possible by their design as a spring element. Therefore the flexible properties of a tube with a thin ring thickness acting in a radial direction can be used. The planet wheel is designed as a thin ring providing simultaneously enough flexibility to compensate errors yet rigid torsional stiffness. The Flexspline is pressed by the planet wheels simultaneously into engagement with the Circular Spline and the Dynamic Spline. Consequently errors in both zones of tooth engagement are compensated by their spring travel.

4. Direct LIG: the production process

The manufacturing of the tiny structural dimensions of the gear wheels of the Micro Harmonic Drive® gear is carried out through photolithographic processes. In order to be able to keep tolerances in the sub micrometer range and simultaneously to feature with the properties of metallic gear wheels the “Direct LIG” process is used. The Direct LIG process is based upon the LIGA process [5] and includes the two steps Lithography and Electroplating (see Fig. 5).



X-ray mask | Lithography | Electroplating | Metal gear wheels | Microsystems

Fig. 5: Steps of the direct LIG-Process

The structures of the gear wheels are situated as a gold absorber layer on an X-ray mask. The mask pattern is copied through a projection step with high precision into a thick photoresist. To be able to manufacture structures of a hight up to 1 mm and simultaneously to keep tolerances less then 1 µm using synchrotron radiation is necessary [6]. After the irradiation the unexposed areas can be developed with a particular solvent. The negative mould of the gear wheels inside the photoresist is galvanically casted by a nickel iron electrolyte. Due to the high yield point of 1.800 N/mm², the low elastic modulus of 135.000 N/mm² and its good fatigue endurance [7] this electroplated alloy possesses the necessary properties for perfect functioning of the flexible gear wheels of this micro gear system.

Beside the extreme high accuracy and the possibility to have a resolution of less micrometers the Direct LIG process offers in opposite to the classical cutting production methods additional new possibilities to shape the profile of a toothing. Using photolithographic production methods there is no need during the design of the profile of gears to consider the kinematics of tools, the fixture during machining or the behaviour of tool wear. Due to the shape is copied through a projection step the freedom of designing in lateral direction much higher. Additionally there is no conjunction between the lateral complexities of the components to be manufactured and the production costs. I.e. the production costs are independently to the number of teeth, whether a inside or outside toothing or both together. However in direction of the third dimension it is only possible to vary the width of the teeth. In this direction it is not possible to vary the shape of the tooth profile.

5. Toothing of the Micro Harmonic Drive® gears

Due to the quite similar tooth number between Flexspline and the both internal gear wheels Circular Spline and Dynamic Spline the Harmonic Drive® gear systems feature with a huge tooth engagement region and a high power density in opposite to other functional principles (see Fig. 6).

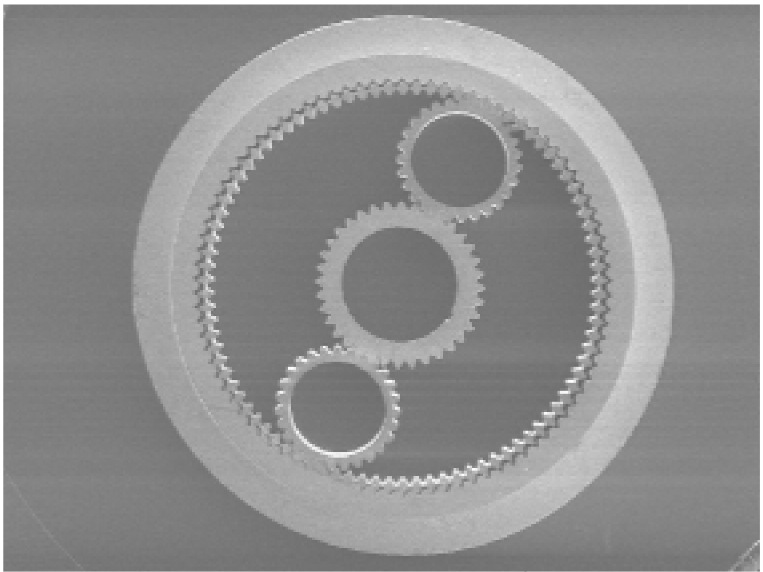


Fig. 6: build up of an Micro Harmonic Drive® gear component set

However the usage of a flexible mechanical transmission element, the so called Flexspline, results in unusual kinematics proportions in a Harmonic Drive® gear system. In opposite to conventional working principles of gear systems the proportion of sliding dominate compared to the proportion of rolling between the toothing of the Flexspline and both internal gear wheels.

In spite of the different kinematics proportions from Harmonic Drive® gear systems this type of gear system is using tooth profiles based on the involute too. The advantages of using the involute for the tooth profile causes from the simply manufacturing and caring of the cutting tools and the possibility to revert to common known calculation schemes by dimensioning.

Disadvantages by using the involute are that the particular kinematics properties of the functional principle of an Harmonic Drive® gear system are not considered in the profile and therefore

- only a smaller tooth engagement region can be realised
- the torque capacity is lesser and
- the efficiency is lesser.

a) b) c)

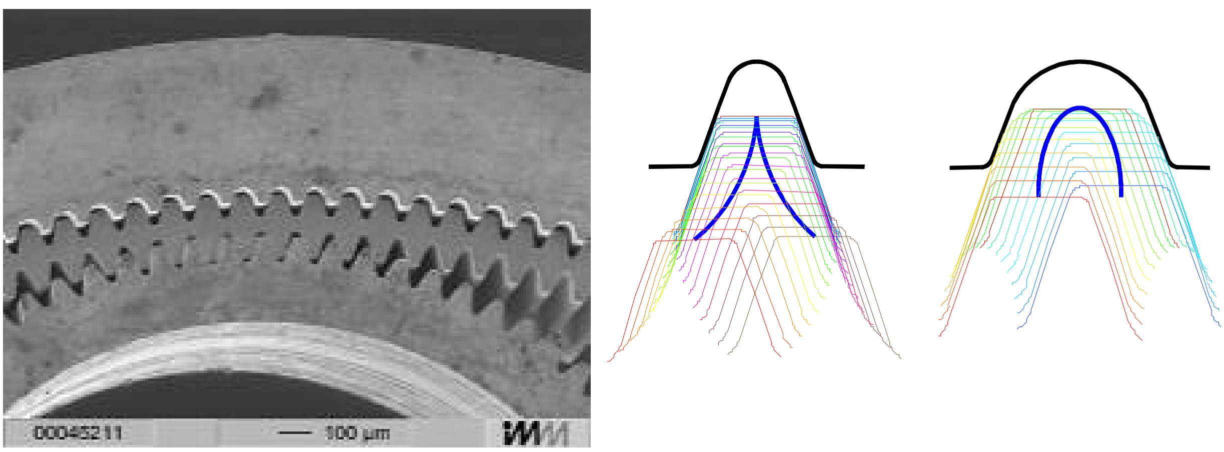


Fig. 7: a) toothing of a Micro Harmonic Drive® with an involute profile, b) simulated motion sequence between Flexspline and Circular Spline, c) Flexspline and Dynamic Spline

In Fig. 7 a Micro Harmonic Drive® gear component set is illustrated using an involute tooth profile with a modulus of 34 µm.

To compensate the disadvantages of an involute tooth profile a novel tooth profile has been developed by the company Harmonic Drive Systems Inc. in Japan. The so-called IH-toothing derivates itself from the kinematics properties of a Harmonic Drive® gear system (see Fig. 8). An important edge condition at the development of the IH-toothing was the need to manufacture this profile by hobbing, shaping and grinding. Due to the fact that this toothing profile considers the particular kinematics properties of a Harmonic Drive® gear system the region of tooth engagement duplicates and therefore it results in a higher torsional stiffness, a increased torque capacity and a significantly increased life expectancy. For Micro Harmonic Drive® gear system purposes the disadvantages of the IH-toothing are that the profile is optimised to the tooth engagement properties of cup type Harmonic Drive® gear systems by using an elliptically ball bearing as Wave Generator. I.e. the tooth engagement between Flexspline and Dynamic Spline as well as the edge condition by using a planetary prestage as Wave Generator are not considered by the dimensioning of the tooth profile.

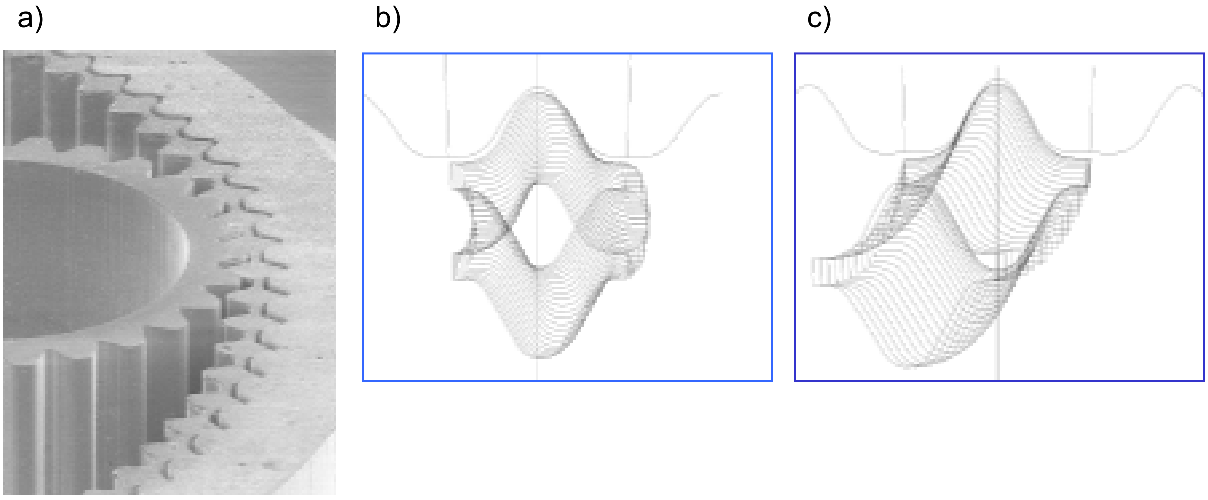


Fig. 8: a) Micro Harmonic Drive® with IH-toothing, b simulated motion sequence between Flexspline and Dynamic Spline, c) Flexspline and Circular Spline

The requirements to the novel P profile for the Micro Harmonic Drive® gear system are based upon the use of a planetary stage as Wave Generator and the built up as a so-called flat type Harmonic Drive® using a second internal gear wheel, the Dynamic Spline. At the novel P profile the shape of the tooth is simultaneously optimised to the kinematics conditions to both the tooth engagement between Flexspline to Circular Spline and the tooth engagement between Flexspline to Dynamic Spline. Another important edge condition is given by the applied production method. Due to the manufacturing is not been carried out with cutting processes the freedoms offering the Direct LIG process are available. The aims of the development of the new profile are the increase of the torque capacity, the torsional stiffness and transmission accuracy.

The derivation of the tooth profiles of the single gear wheels is been carried out about the calculation of the geometry of deflection of the elastically deformed Flexspline. The motion sequence between Flexspline to Circular Spline and Flexspline to Dynamic Spline calculates from the geometry of deflection of the Flexspline. Based upon these two motion sequences it is possible to derivate the profile of the toothing of the flexspline. Afterwards this profile which is derivated straight from the kinematics of the gear system is provided with corrections in the regions of the bottom and the top (see Fig. 9).

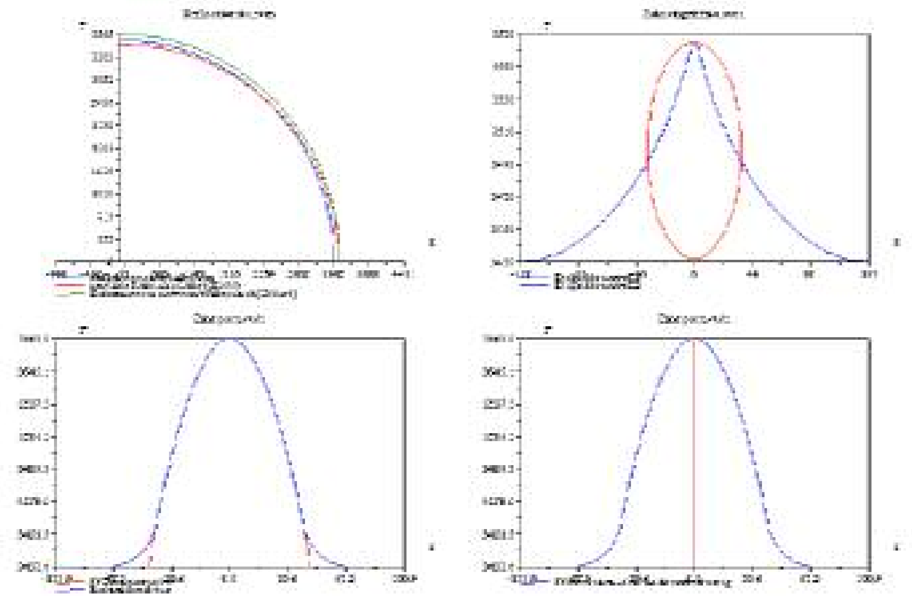


Fig. 9: single steps to derivate the profile of the flexspline

The derivation of the profile of the Dynamic Spline and Circular Spline is based upon the tooth profile of the Flexspline and the respective motion sequences. The envelopes representing the tooth profile of the Dynamic Spline and Circular Spline can be calculated from both the tooth profile of the Flexspline and its motion sequences. Afterwards the tooth profile of Circular Spline and Dynamic Spline is provided with corrections in the regions of the bottom and the top (see Fig. 10).

a) b)

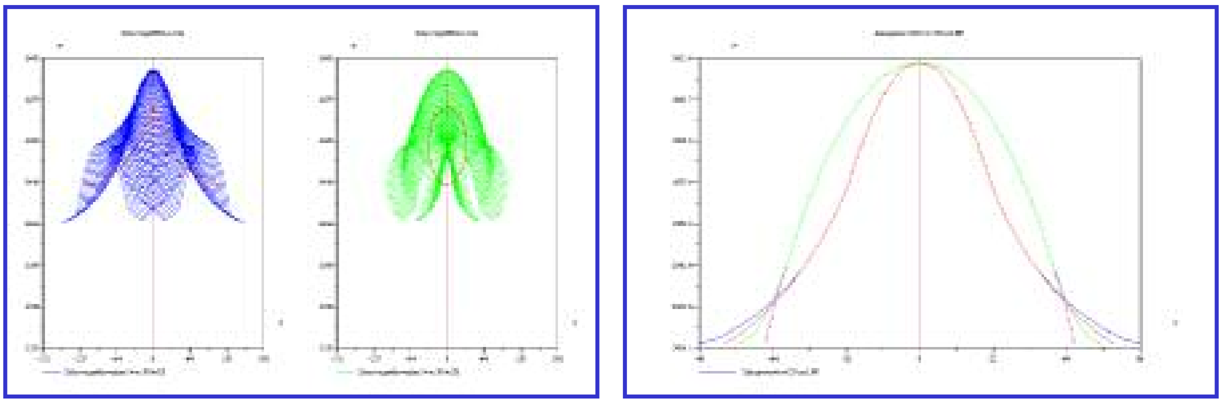


Fig. 10: derivation of the tooth profiles of the Circular Spline and the Dynamic Spline

The proceeding to derivate the tooth profile of the gear wheels of the planetary prestage is carried out analogue to the proceeding by Dynamic Spline and Circular Spline and is based upon both the motion sequence and the profile of the internal toothing of the Flexspline. Thereupon the profiles of the planetary gear wheel and the sun gear wheel are provided with corrections in the regions of the bottom and the top (see Fig. 11).

a) b)

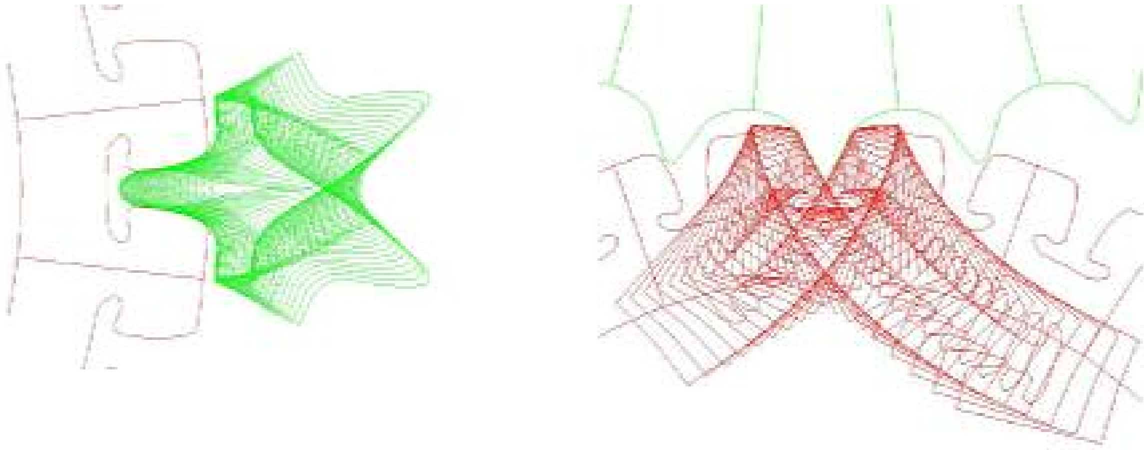
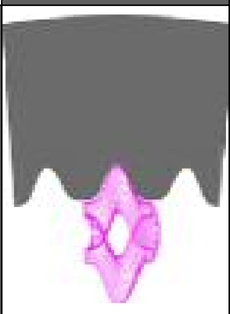
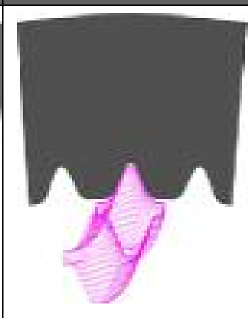
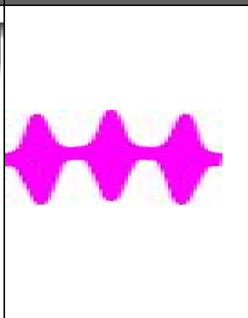
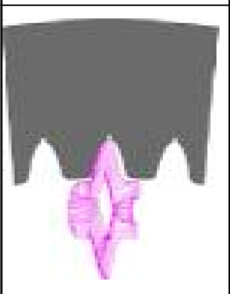
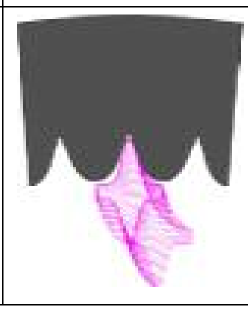
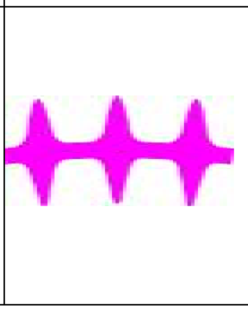


Fig. 11: derivation of the tooth profiles of planetary Wave Generator

The shapes of the single gear wheels of a Micro Harmonic Drive® gear system with an IH tooth profile are opposed in Table 1 to one with a P tooth profile.

Table 1: Geometrical comparison between IH and P profile

	Dynamic Spline	Circular Spline	Flexspline	Planet wheel	Sun wheel
IH profile					
P profile					

The aims of the optimizations of the profile of the Flexspline are following:

- the increase of the tooth engagement region additionally between Flexspline and Dynamic Spline,
- the optimization of tensions inside the Flexspline and
- the increase of flexural stiffness of the Flexspline.

The optimised P profile for the toothing of the Flexspline of a Micro Harmonic Drive® gear system is illustrated in Fig. 12. The increase of the addendum results in a bigger tooth engagement region. The decrease of tooth thickness reduces the mechanical tensions inside the ring of the Flexspline and allows increasing the ring thickness and therefore the flexural stiffness of the whole Flexspline.

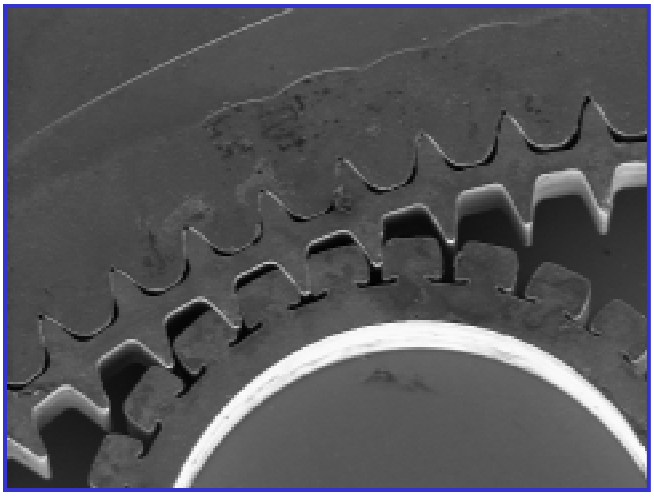


Fig. 12: optimised toothing of the Flexspline

Due to the optimizations at the tooth profile of the Dynamic Spline and the Circular Spline the following properties could be realised (see Fig. 13):

- increased tooth engagement region,
- well-defined regions for running in and running out
- well-defined regions of contact and guiding the Flexspline
- well-defined shaping of the clearance

a) b)

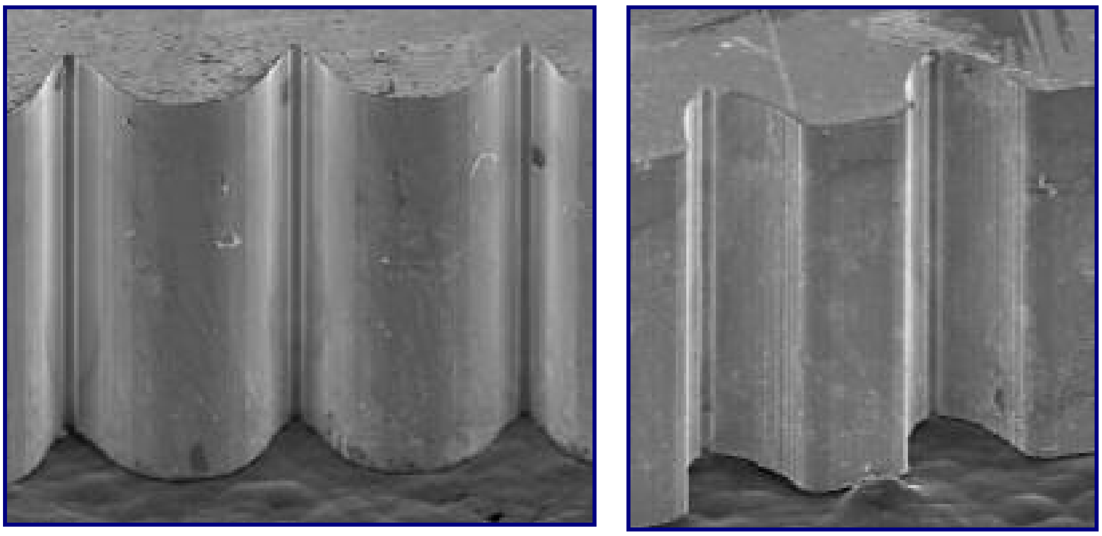


Fig. 13: optimised toothing of a) Circular Spline and b) Dynamic Spline

Due to the small thickness of the Flexspline toothing it is necessary to realise a big tooth thickness of the planetary gear wheel. However this required tooth thickness conflicts with radial flexibility of the planetary gear wheels. To be able to set up the radial spring properties of the planetary gear wheel independently from the tooth profile there are undercuts integrated in the region of the tooth root (see Fig. 14).

a) b)

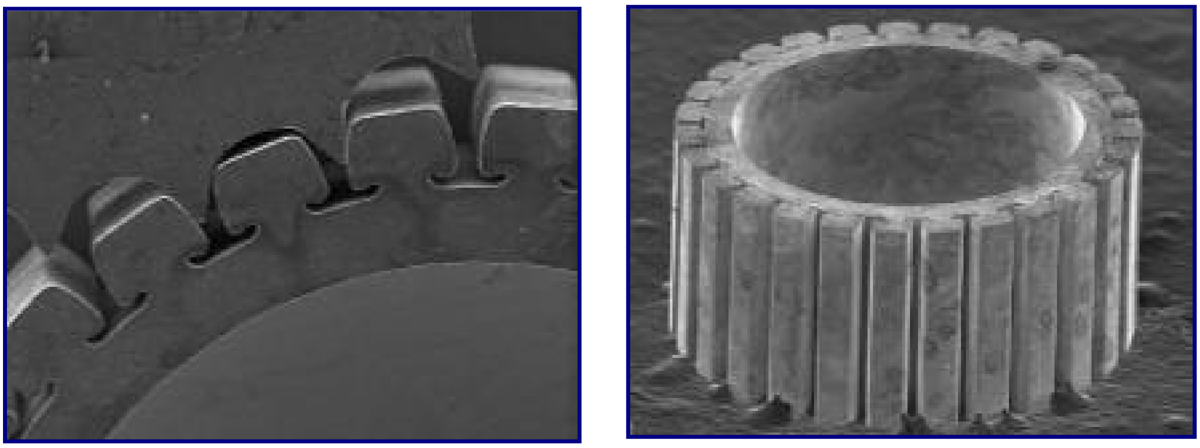


Fig. 14: optimized toothing of the planetary gear wheel

The complete component set of a Micro Harmonic Drive® gear with realized P profile is illustrated in Fig. 15.

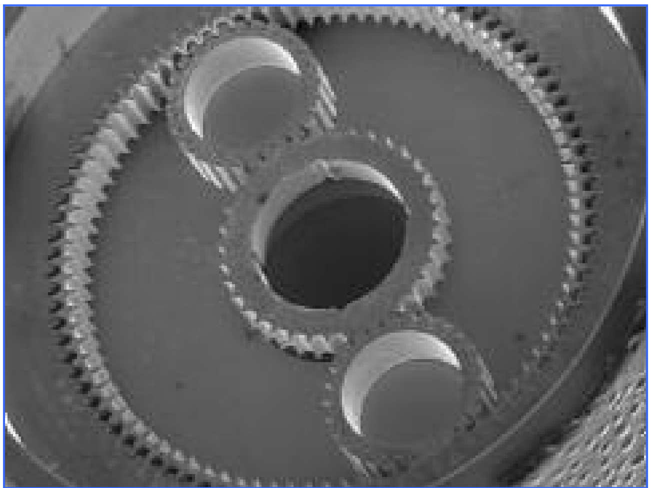


Fig. 15: component set of an Micro Harmonic Drive® gear with transmission ratio 160 : 1 featured with the optimized P profile

In first experimental investigations with the P profile there could be fulfilled measurements about the torque capacity, the friction torque, the torsional stiffness and the efficiency. The measurements are carried out with a gear box of the size MHD-10 with a transmission ratio of 160 : 1: MHD-10-160-PH. The ratcheting torque, i.e. the torque deforming the gear wheels so much coming out of engagement, achieves with the P profile values over 95 mNm. That accords to an increase of torque capacity about approximately 200%. The friction torque of the input shaft keeps at approximately 20 µNm furthermore. The trend of the curve of efficiency in relation to the output torque is illustrated in Fig. 16.

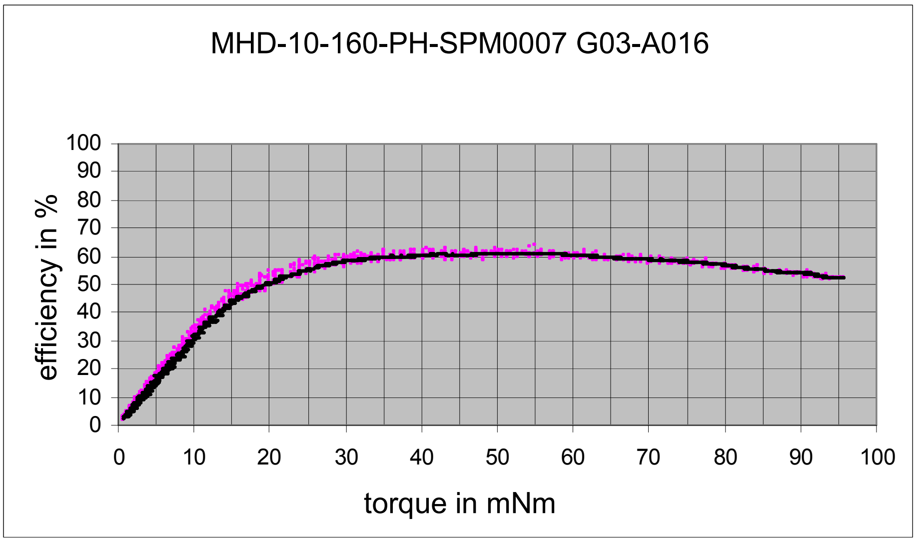


Fig. 16: curve of efficiency in relation to the output torque

Fig. 17 illustrates the result of the measurement of the hysteresis curve. The hysteresis curve is acquired by applying a torque to the output shaft with the input rotationally locked. The hysteresis curve describes the relationship between the torque and the angle of torsion.

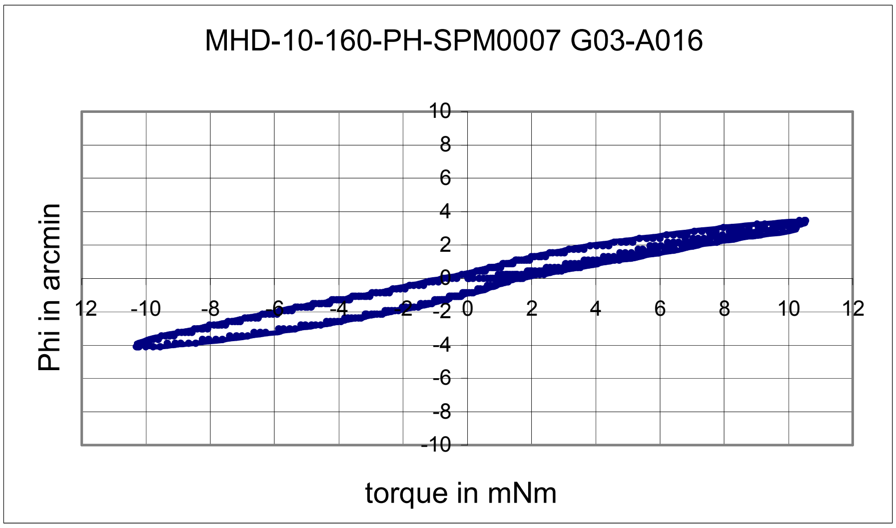


Fig. 17: hysteresis curve of the MHD-10-160-PH

The value of the hysteresis loss accounts for the measured gear box about 1.5 arcmin. The measured gear box has a torsional stiffness of 10 Nm/rad.

6. Advantages of the Micro Harmonic Drive® gears

The use of the Micro Harmonic Drive® gear provides the machine designer with numerous advantages:

a) Miniature dimensions yet zero backlash

The Harmonic Drive® gear stage is backlash-free by nature and the elastically deformable planet wheels eliminate backlash in the planetary stage.

b) Excellent repeatability for precise positioning

The zero backlash of the Micro Harmonic Drive® gear provides a repeatability in the range of a few seconds of arc. This enables positioning tasks to be carried out with sub-µm accuracy

c) High dynamic performance for fast indexing applications

The high torque capacity and low moment of inertia enable extremely fast accelerations of up to 550 000 rad/s2 at the input shaft. This corresponds to an acceleration of the motor shaft from 0 to 100 000 rpm in 25 milliseconds. This, in turn, enables extremely fast angular movements e.g. a rotation of 180 ° in less than 80 milliseconds.

d) Very long operating life

The MHD micro-gearboxes have an operating life of 2500 hours at rated operating conditions, that is, at rated input speed and rated output torque. This corresponds to many million operating cycles in practical applications and the operating life of the micro-gearbox is typically equivalent or longer than the expected operating life of the machine in which it is used. The “life-cycle-costs” are therefore considerably lower than for other solutions with a lower initial cost.

e) Very high reliability

The MHD gearbox has a significantly higher MTBF (**M**ean **T**ime **B**etween **F**ailure) rating than other microgears. This is mainly the result of the far lower number of parts, compared to other gears. A planetary microgear with a reduction ratio of 1000:1 typically has 25 individual gear wheels, whilst the comparable Micro Harmonic Drive® gear has just 6.

f) High efficiency to avoid power losses

The Micro Harmonic Drive® gear has an efficiency of up to 82% at rated operating conditions. This is also significantly higher than for other micro-gears. The reason lies in the small number of tooth engagement areas. A planetary gear with ratio 1000:1 has 30 regions of tooth engagement, whilst the comparable Micro Harmonic Drive® has just 8.

g) Extremely flat design for compact gearbox dimensions

The axial length of the MHD micro-gearbox is independent of the reduction ratio and is less than half the length of other micro-gearboxes for the same output torque and reduction ratio.

h) Low mass for applications in portable devices or in moving structures

As can be seen from Table 1, the gearboxes weigh just a few grams. In practical applications this means that the moving masses in the machine can be minimised. This, in turn, can contribute to greater thermal stability and lower temperature rise, both of which are essential in high precision machines. Furthermore, this enables higher accelerations and/or smaller feed drives.

i) High reduction ratios for low-loss torque conversion and easy control

The high reduction ratios greatly reduce the load moment of inertia reflected at the motor shaft. The result is that in most practical applications the motor is hardly influenced by the load inertia. In combination with the low input-side moment of inertia of the gear this has the effect that the control of the motor is almost independent of the load inertia over a very large range of load inertias. This makes the control of the motor and setting-up of the control system very easy.

j) Hollow shaft capability

The optional hollow shaft can be used to pass laser beams, air / vacuum supply or optical fibres through the centre of the gear or actuator along the central axis of rotation. This can greatly simplify the design of machines where otherwise the laser beam or fibre would need to be diverted around the actuator.

k) Robust, accurate output bearing arrangement

The high load capacity of the output bearings (preloaded ball bearings in an O-configuration – see Fig. 2) mean that no additional support bearings are needed for the load in most applications. Furthermore, the accurate geometric tolerances (axial and radial run-out less than 5 µm) allow the attachment of load components e.g. mirrors, filters or lenses, directly to the output shaft.

l) Applicable under extreme environmental conditions

The use of high quality materials, such as stainless or high-alloy steels for the gearbox housing, input / output shafts and bearings, provides a high level of corrosion resistance, even for standard MHD micro-gearboxes. The Micro Harmonic Drive® gear, which is manufactured in a high strength Nickel-Iron alloy, can be sterilized and can be used over a very wide temperature range (-20° C - +150° C). It can also be applied in a vacuum [8], using grease, oil or dry lubrication, depending on the specific requirements of the application.

This combination of features makes the Micro Harmonic Drive® gearbox very attractive for precise assembly applications. The high repeatability means that components can be orientated with very high accuracy, while the high dynamic performance means that assembly speed must not be sacrificed.

7. Outlook

Micromotion GmbH is continuing to develop the Micro Harmonic Drive® gear in order to further improve its performance. With the novel P profile the peak torque can be doubled, which will enable even more dynamic positioning cycles and so reduce assembly cycle times even more.

As next steps it is planed to make the P profile also available to the transmission ratios 500 : 1 und 1000 : 1 and to carry it forward to the next smaller size, the MHD 8.

8. Reverences

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