Title: The Micro Harmonic Drive gear

1. Introduction:

The overall trend to miniaturisation in many fields has led to the development of several kinds of micromotors as the basis for powerful micro actuators [1], [2], [3]. In the past few years a considerable number of different micro motors have been realized to fulfil customer's demands in a variety of different areas of application. The other key constituent element of powerful micro actuators is represented by the gear system. Most currently available micro motors are characterized by very high rotational speeds and very low rated torque. Therefore, a gear is often necessary in order to adapt these characteristics to real-world applications, which need higher torques and lower speeds. A wide range of different gear types exists for micro motors, e.g. several types of planetary gear systems [4] or spur gear systems [5].

At Micromotion GmbH in Mainz, Germany, an affiliated company of Harmonic Drive AG of Limburg, Germany, the principle of operation of a Harmonic Drive® gear system has been applied to a micro gear system of only 1 mm axial length and 6 or 8 mm diameter using a modified LIGA technique (see Figure 1.1). 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.

Figure 1.1: Micro Harmonic Drive® gearbox and actuator

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 of up to 100.000 rpm and very low output torques in a range of some µNm provided by current 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 continuously improved to allow the cost effective manufacture of metallic 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.

The advantages of miniaturization, e.g. low masses, low power consumption and small dimensions open new fields of applications for powerful micro actuators in dynamically growing markets. Innovative fields for micro gear motors arises e.g. in medicine, aerospace, automated assembly and consumer industry. In addition to their miniaturized size and low weight micro gear systems must also feature zero backlash and precise angular transmission.

With a repeatability and lost motion of less than 10 arcseconds the Micro Harmonic Drive® is ideally suited for applications in high precision micro positioning drive systems. This unique micro gear is also the basis for the world's smallest backlash free servo actuator, developed in cooperation with Maxon Motor AG of Switzerland.

Since its market introduction in 2001 the Micro Harmonic Drive® has successfully made the transition from laboratory into industrial applications (see Figure 1.2). The micro gears and micro actuators are already successfully used in micro-robots, semiconductor manufacturing equipment and even in spacecraft.

Figure 1.2: Prototype of the Micro Harmonic Drive® gear

Until now most machines for precision assembly tasks have been many orders of magnitude larger than the workpieces to be handled or necessary workspace. Micromotion GmbH, in co-operation with the Institute of Machine Tools and Production Technology at the Technical University of Braunschweig has now developed a small-scale SCARA robot featuring a parallel hybrid kinematic structure. This new robot, with a base area of less than 150 x 150 mm² can position small workpieces with a mass of up to 50 g with a repeatability of better than 10 µm (see Figure 1.3).

Figure 1.3: "Parvus" Micro-Robot

In the remaining chapters of this paper the basic principle of operation and components of the Micro Harmonic Drive® gear will be described. The unique "Direct-LIG" manufacturing process will also be described in detail, as well as practical test results documenting the excellent performance of this micro-technological product. Finally, a number of industrial applications are presented to demonstrate how this novel product has made the transition from laboratory to industrial practice in a very short space of time. The Micro Harmonic Drive® gear is now establishing itself as a key enabling technology on the path to the desktop factory.

2. From Mini- to Micro Harmonic Drive® gears

The trend to miniaturization cannot be overseen. The use of very small electronic and electro-optical components in a variety of consumer and investment goods is leading to an increasing demand for small-scale servo actuators for micro assembly applications in production equipment. As soon as miniaturised systems and hybrid microsystems need to be manufactured in large series there is a requirement for automated assembly. For small scale products of this type the assembly process is often a major cost-driver, making up to 80% of total production costs [6]. Manual assembly is either too expensive, or does not achieve the required process stability. Automated micro assembly requires, in turn, specialised production equipment for handling miniature components. The assembly process typically requires movements in several degrees of freedom, which are enabled by power transmission components, such as motors, gears, ballscrews etc.

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. 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.

Figure 2.1: Comparison between the smallest conventionally manufactured Harmonic Drive gear and a Micro Harmonic Drive gear component set

Micro gear systems represent a key element in micro drive systems. Micro-gears 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.

a) b)

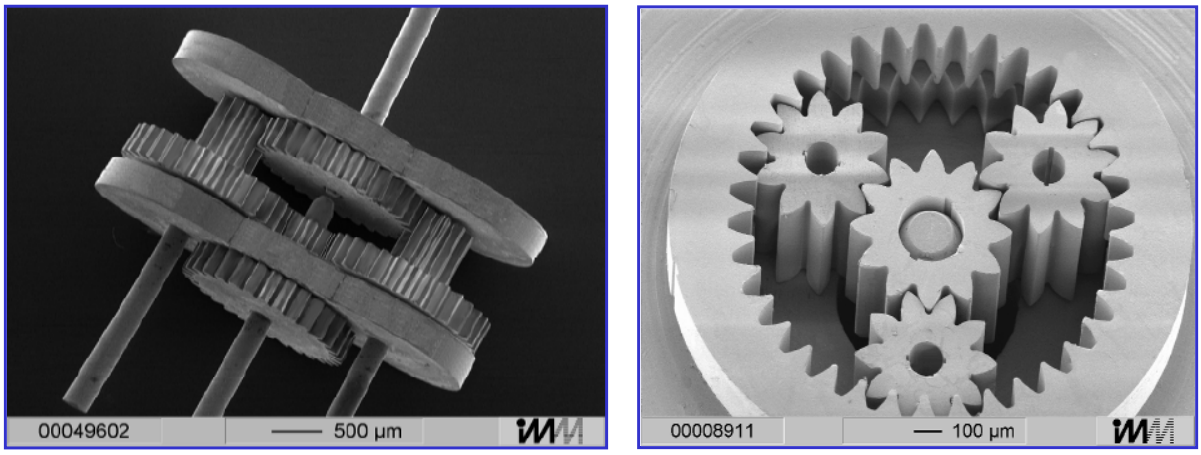

Figure 2.2: a) Micro spur gear with two trains
b) Micro planetary gear system

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 [7]. Until now there have been no micro-gears suitable for precise positioning applications. Micro gear systems must not only be extremely small, but also exhibit the following features:

- A high repeatability,
- Zero backlash,
- A high reduction ratio and
- A low parts count.

The solution is the principle of a Harmonic Drive® gear system. This kind of gear system stands out compared with other gear principles e.g. spur gears (see Figure 2.2 a) and planetary gear systems (see Figure 2.2 b), because of its high precision and zero backlash transmission properties. Its exceptional properties have been proven for many years in the fields of industrial robots, machine tools, measuring machines, aerospace and medical equipment [8], [9]. Harmonic Drive® gear systems can be classified into the flat type and the cup type. The flat type gear system offers the following advantages, which are particularly important with reference to micro gear systems:

- Small number of components,
- A compact design and
- The high reduction ratio necessary for micro motors can be reached in a single gear stage.

Only by using suitable micro gear systems it is possible to apply existing micro motors 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®.The Micro Harmonic Drive® gear is currently the world's smallest zero backlash gear and in combination with a specially developed motor from Maxon Motors, Switzerland, forms part of the world's smallest zero backlash positioning actuator (see Figure 2.3).

Figure 2.3: World's smallest zero backlash actuator (diameter 8mm, length 31,3 mm)

The Micro Harmonic Drive® gear was introduced into the market in 2001 as the world's smallest backlash-free micro gear. It is manufactured using a modified LIGA process, called Direct-LIG (see Figure 2.4). This allows the cost-effective production of extremely precise metallic gear components. In the meantime this gear has been implemented in a range of miniaturized servo actuators, which provide zero backlash, excellent repeatability and long operating life.

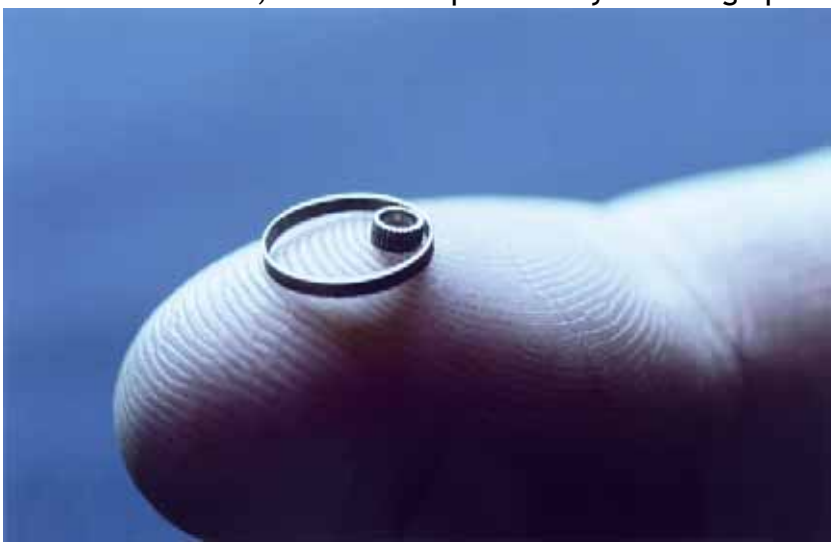

Figure 2.4: Micro Gear Components

The Micro Harmonic Drive® gear component set has an outer diameter of just 6 or 8 mm and an axial length of 1 mm. 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. 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.

3. Principle of operation

To construct a gear with the operating principle of a "Harmonic Drive" there are two design alternatives (see Figure 3.1): the cup-type design and the flat-type design. The flat-type design is ideal to realize a ultra flat micro gear system with a high reduction ratio.

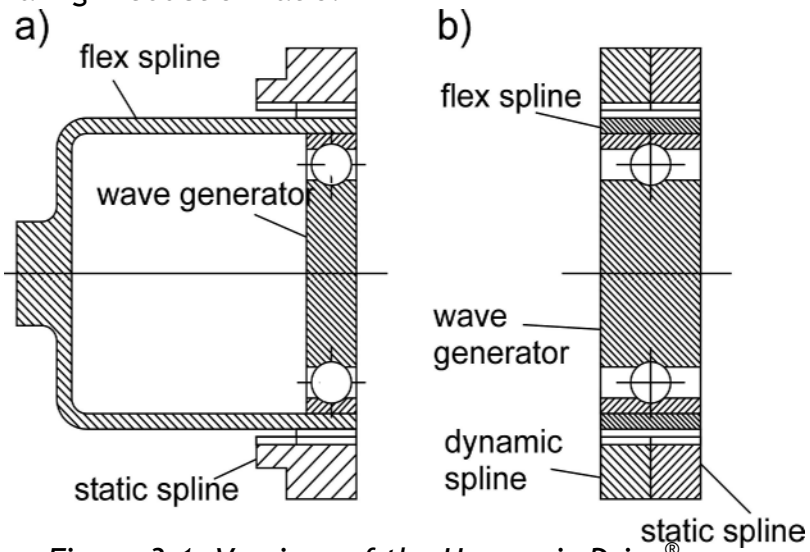

Figure 3.1: Versions of the Harmonic Drive® gear: a) Cup type, b) Flat type

The basic elements of the flat type Harmonic Drive® gear system are the elliptical Wave Generator and the three gear wheels

- Flexspline,
- Circular Spline and
- Dynamic Spline.

There are three basic configurations for the Wave Generator: an elliptical ball bearing, a planetary gear arrangement and a two roller link (see Figure 3.2).

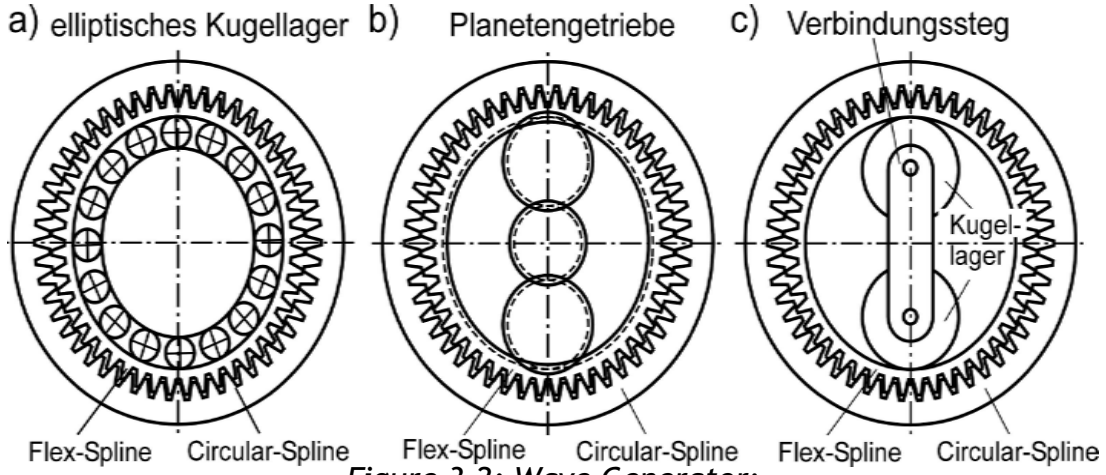

Figure 3.2: Wave Generator:
elliptical ball bearing, b) planetary gear, c) two roller link

With respect to the miniaturization of the Micro Harmonic Drive® the planetary gear configuration for the Wave Generator possesses the following advantages:

- All gear components can be manufactured using the high precision LIGA-technique
- The assembly effort can be minimized, because the Wave Generator consists of only three components
- The total reduction ratio of the gear increases due to the planetary gear. This design can therefore flexibly adapt the very high rotational speed of micro motors in only one stage to the specific requirements of a given application
- This variant of the Wave Generator possesses only a low moment of inertia and therefore enables a highly dynamic positioning performance

By using a planetary gear for the Wave Generator it is possible to vary the total ratio of the Micro Harmonic Drive® over a large range.

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 (see Figure 3.3). 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 Figure 3.4). Across the minor axis of the elliptically deflected Flexspline there is no tooth engagement.

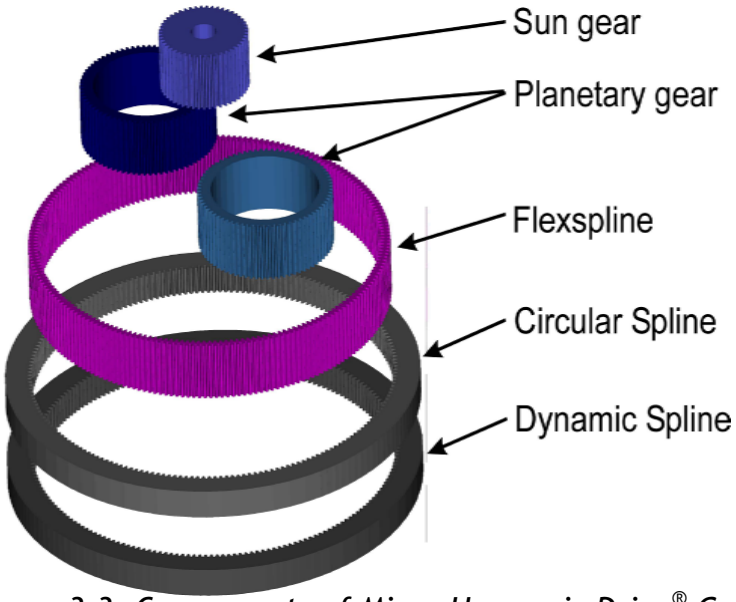

Figure 3.3: Components of Micro Harmonic Drive® Gear

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. A small difference in the number of teeth between the Flexspline and the Circular Spline (the latter has two teeth more) 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.

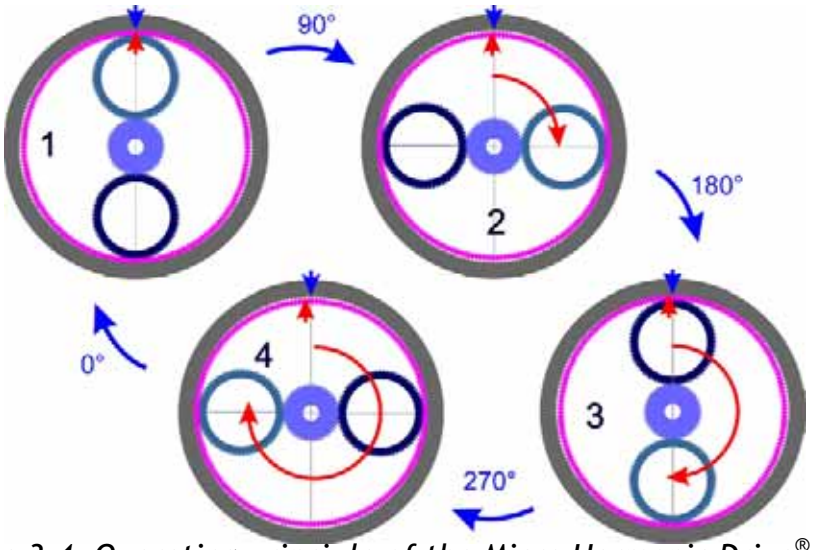

Figure 3.4: Operating principle of the Micro Harmonic Drive® gear

A gear module down to 34 µm must be used to realize the necessary high reduction ratio and the small dimensions simultaneously. The single gear wheels of the Micro Harmonic Drive® are manufactured by electroplating and consist of a nickel-iron-alloy. Due to the high yield point of 1.500 $^{N}/mm^2$, the

low elastic modulus of 165.000á^{N}/mm^{2} and its good fatigue endurance [10] this electroplated alloy possesses the necessary properties for perfect functioning of the flexible gear wheels of this micro gear system.

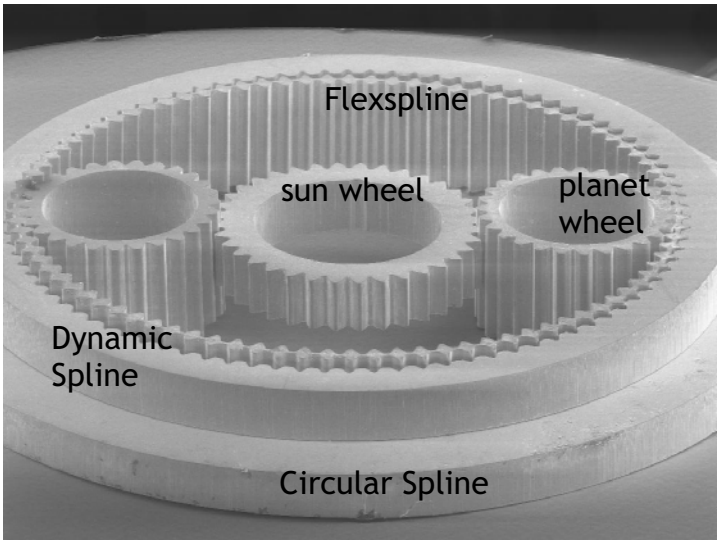

Figure 3.5: Components of the Micro Harmonic Drive® Gear

The Micro Harmonic Drive (see Figure 3.5) offers the following advantages, which are particularly important with reference to micro gear systems:

- Zero backlash yet miniaturized dimensions,
- Excellent repeatability,
- High torque capacity,
- Only six components and therefore a high reliability,
- High efficiency,
- Extremely flat design,
- Low weight,
- Compact dimensions and
- The high reduction ratio necessary for micro motors can be reached in a single gear stage.

By using a planetary gear for the Wave Generator it is possible to vary the total ratio of the Micro Harmonic Drive® over a large range. For the shown gear size, reduction ratios from 160 up to 1000 can be realized in a single stage.

3.1. Flexible gear wheels

3.1.1. The Flexspline

The Flexspline represents the most challenging component of the Micro Harmonic Drive® (see Figure 3.6).

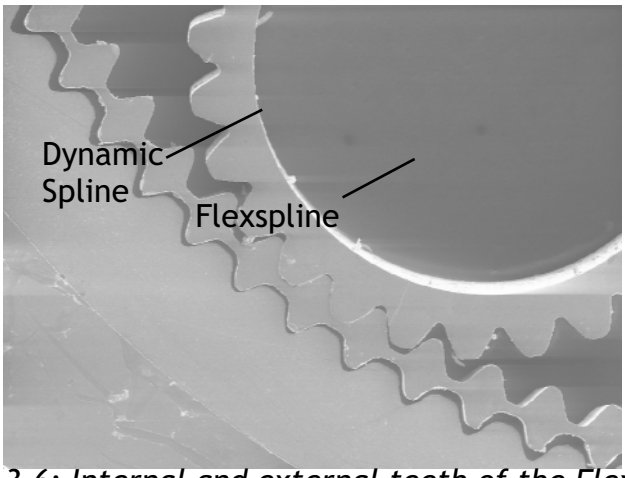

Figure 3.6: Internal and external teeth of the Flexspline

Contrary to conventional gear systems based on the Harmonic Drive® operating principle, the Flexspline of the Micro Harmonic Drive® needs in addition to its very thin ring thickness both internal and external teeth. This duplex toothing is necessary due to the planetary gear configuration of the Wave Generator. To achieve trouble-free operation the Flexspline must exhibit uniform deflection behaviour. This is realized by using the same number of teeth for the external and internal toothing. The production of the duplex toothing and the thin ring thickness necessary for low bending stresses when the Flexspline is deflected is made possible by using the LIGA-technique [11]. Because of this technique it is possible to realize a ring thickness in the tooth root down to only 26 µm for a tooth width of 1000 µm.

3.1.2. Planetary gear wheels

Another component contributing essentially to the zero backlash and precise operating behaviour of the Micro Harmonic Drive® is the flexible planet wheel of the Wave Generator. Both 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 simul-

taneously into engagement with the Circular Spline and the Dynamic Spline. Consequently errors in both zones of tooth engagement are compensated by their spring travel (see Figure 3.7).

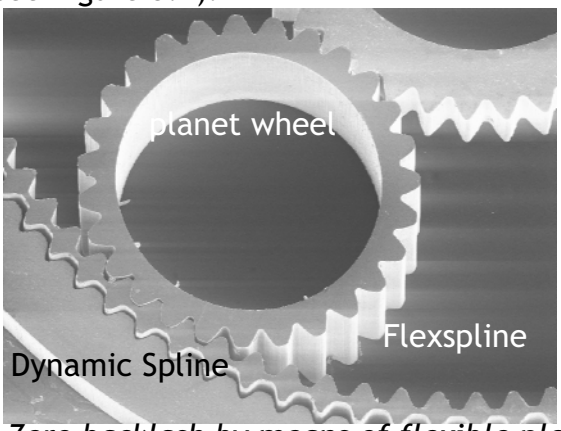

Figure 3.7: Zero backlash by means of flexible planet wheels

As a result both external and internal teeth of the Flexspline are brought into contact with the leading and return faces of the teeth of the meshing gear wheels. The preload of the gear system provided by the flexible planet wheels is the basis for the zero backlash transmission behaviour and high positioning precision of the Micro Harmonic Drive®.

3.2. Simulation of the ultra flat gear

The design of the geometry of the tooth flanks of the gear wheels Flexspline, Circular Spline and Dynamic Spline represents a key stage in the dimensioning of the Micro Harmonic Drive gear. In contrast to conventional gear systems the relative meshing of the Flexspline and Circular Spline teeth involves not a rolling but a primarily radial movement. To be able to execute an exact dimensioning of the teeth, in particular of the geometry of the flanks, it is necessary to compute the exact curves of movement of the Flexspline teeth in relation to the Circular- and Dynamic Spline (see Figure 3.8).

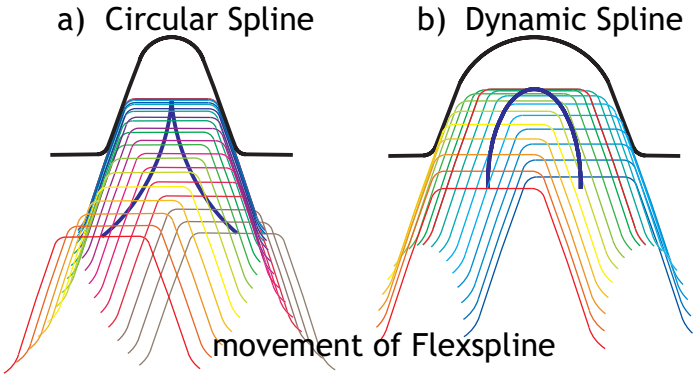

Figure 3.8: Relative meshing of Flexspline with a) Circular Spline and b) Dynamic Spline

These curves of movement serve as basis for an exact dimensioning of the teeth of all the gear wheels of the Micro Harmonic Drive®. Thereby a trouble-free function of the gear system and the precision of movements needed for positioning drive systems can be realized.

The main goal of the FEM analysis was to dimension the flexible wheels of the gear system: the flexspline and the planet wheels. The deformed gearwheels have been examined by FEM analysis to determine occurring stress exactly. The results of the maximum stress in Flexspline and the planet wheel are shown in Figure 3.9a and Figure 3.9b. The data of the nickel-iron (NiFe) alloy and fatigue strength serve as basis of the analysis. As a result of the geometrical optimization of the gearwheels a maximum stress of about 100 N/mm^2 and 120 N/mm^2 respectively could be reached, which is well below the fatigue strength of NiFe (600 N/mm^2).

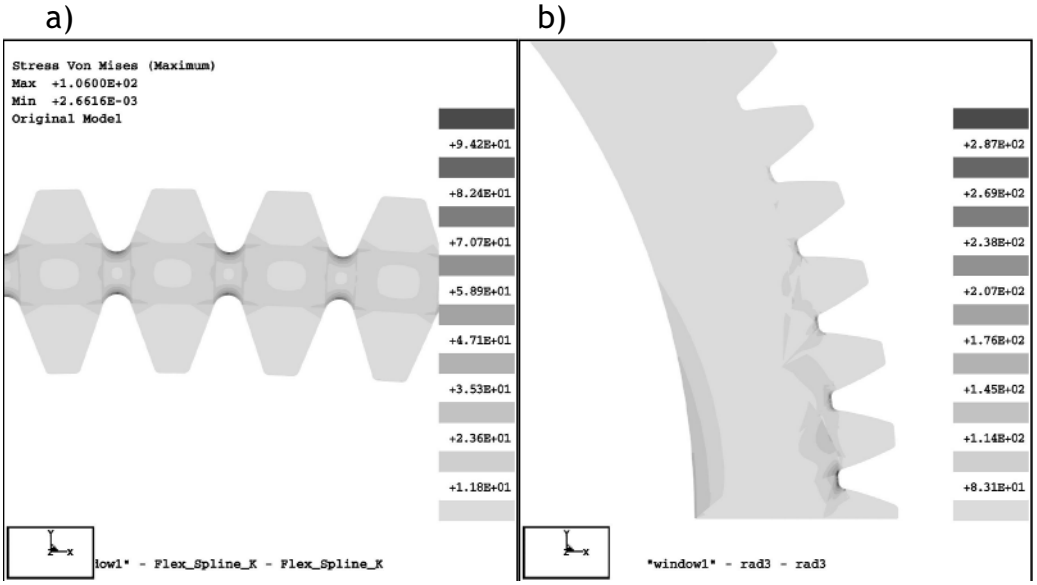

Figure 3.9: FEM analysis: a) stress in flexspline, b) stress in planet gear

The optimization of the geometrical dimensions of the flexible gear wheels of the Micro Harmonic Drive® was executed by FEM analysis.

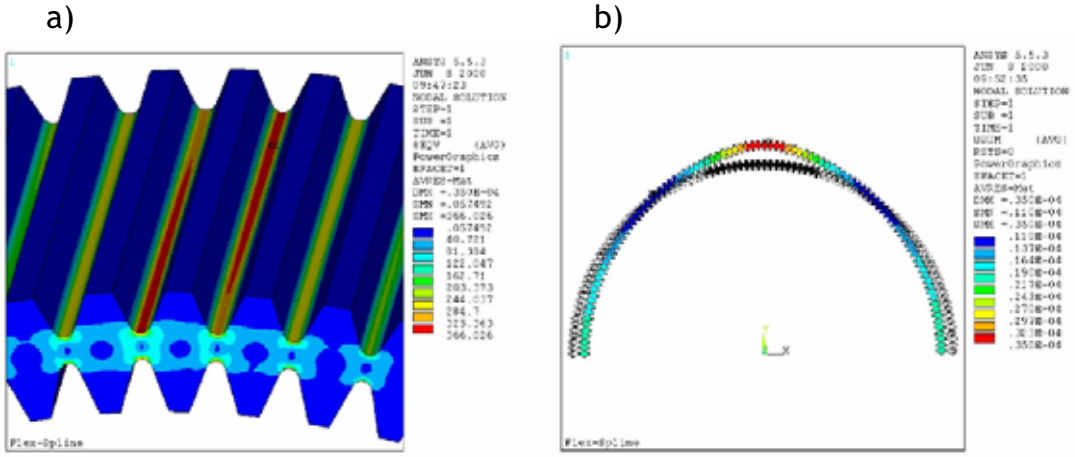

Figure 3.10: a) Stress under load, b) Deflection of the Flexspline

The mechanical stress in the Flexspline resulting from the deflection through the wave generator and an external torque load can be exactly determined in dependence of the geometrical dimensioning (see Figure 3.10a). Additionally the FEM-simulation allows the exact calculation of the deflection of the loaded Flexspline (see Figure 3.10b).

4. Properties of Micro Harmonic Drive® gears

4.1. Hollow shaft

Due to its special design the Micro Harmonic Drive® offers not only the possibility to realize a very high transmission ratio without backlash. Another important property for systems which are optimized with respect to their outer dimensions is the possibility to realize a hollow shaft. This means that a hollow shaft can be passed straight through the gear system along the central

rotational axis. This hollow shaft, which passes through the sun gear (see Figure 4.1) is important for a wide range of different functions.

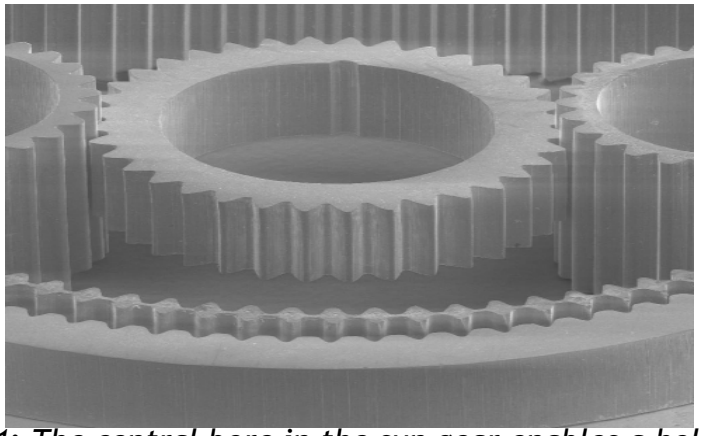

Figure 4.1: The central bore in the sun gear enables a hollow shaft

Especially in the field of devices optimized with respect to outer dimensions the possibility of a hollow shaft offers significant opportunities to reduce the outer dimensions of the whole system. Different kinds of signals or media needed for the application can be transported through the hollow shaft. The hollow shaft can be used e.g. for sensors or for optical fibers. Additionally vacuum or air can be transmitted through the hollow shaft to the output side of the gear.

4.2. MHD micro-gearbox range

The gear component set is typically mounted inside a gearbox (see Figure 4.2) with an output shaft mounted in pre-loaded ball bearings. The gearbox can either be directly coupled to a micro-motor, or can be provided with an input shaft, so that the motor can be mounted off-axis

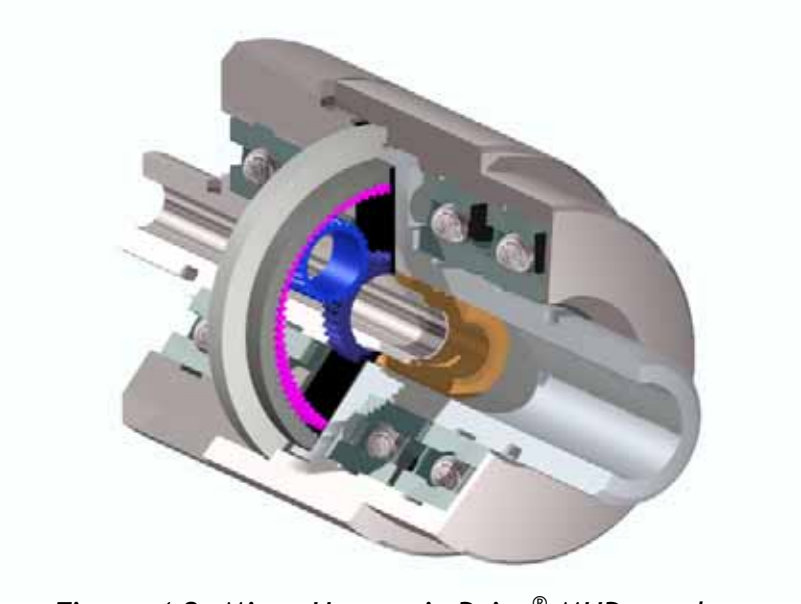

Figure 4.2: Micro Harmonic Drive® MHD gearbox

Two sizes of the MHD micro-gearbox have been developed:

- MHD 8
- MHD 10

The MHD 10 model uses the a gear component set with an outer diameter of 8 mm. The MHD 10 model has a housing diameter of 10 mm and a centering shoulder of 9 mm serving simultaneously for axial location. The MHD 10 model is provided with the reduction ratios 160, 500 and 1000 and can be built up both with and without hollow shaft (see Figure 4.3).

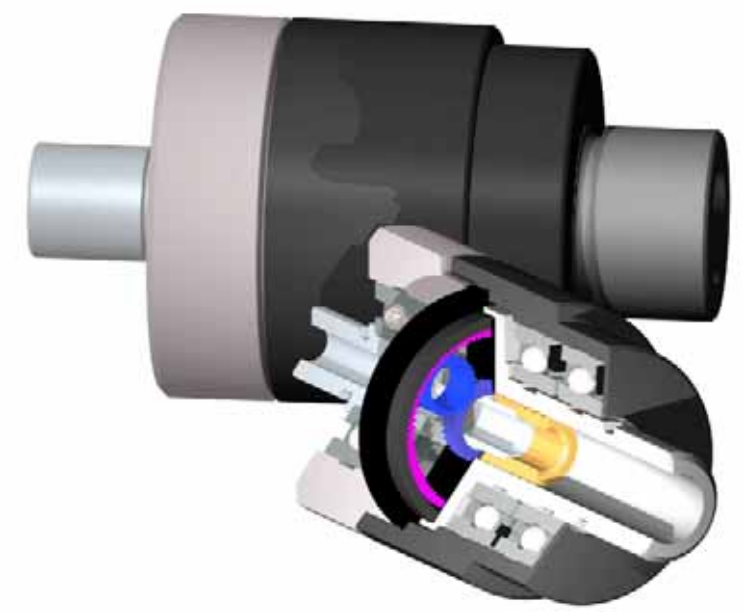

Figure 4.3: The new micro-gearbox models: MHD 10 and MHD 8 shown as unit with hollow shaft

The MHD 8 model uses a newly developed and further miniaturized gear component set with an outer diameter of only 6 mm. The MHD 8 model features a housing diameter of 8 mm with a centering shoulder of 7 mm. The reduction ratios 160 and 500 are available for this model. A version with hollow shaft is also available for this gearbox size. Both models are available as a unit with an input and output shaft or directly coupled with several types of currently available micro motors.

4.3. Experimental analysis and data

The very low friction torque of this zero backlash micro gear system is based on the exact dimensioning of the gear wheels and the high precision reached by using the LIGA-technique for manufacture. In spite of the pre-load of the wave generator, which is necessary to realize a zero backlash gear system, the maximum measured friction torque is only 16 µNm (see Figure 4.4a).

The measured maximum value of the efficiency of the Micro Harmonic Drive® gear amounts to 40 % for a transmission ratio of 500 (see Figure 4.4b).The measuring results illustrated in Figure 4.4b show the steady increase of the efficiency with increasing output torque. Due to the monotonic increasing trend of the measured points and the progress of the theoretical curve a further increase of efficiency may be expected towards still higher torques

a) b)

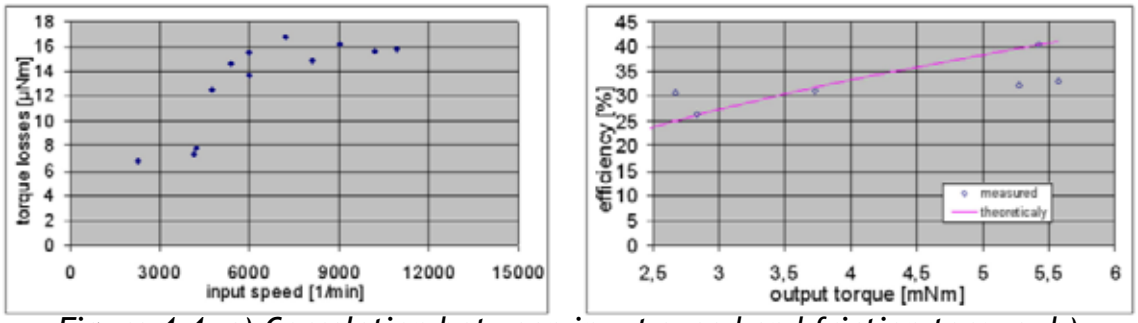

Figure 4.4: a) Correlation between input speed and friction torque, b) Correlation between output torque and efficiency

The measured maximum value of the efficiency of the Micro Harmonic Drive® gear amounts to 40 % for a transmission ratio of 500 (see Figure 4.4b).The measuring results illustrated in Figure 4.4b show the steady increase of the efficiency with increasing output torque. Due to the monotonic increasing trend of the measured points and the progress of the theoretical curve a further increase of efficiency may be expected towards still higher torques

Additionally to its low friction torque and high efficiency the Micro Harmonic Drive® is distinguished especially by its excellent transmission qualities in comparison to other gear systems. The repeatability, lost motion and the hysteresis are suitable criteria to describe the quality of the transmission of a zero backlash gear system operating in positioning drive systems. The hysteresis describes the effects of a changing output load of the angular position of the output shaft of the gear and simultaneously its torsional stiffness. The value of the lost motion describes the angular error, which results by positioning movement from opposite directions.

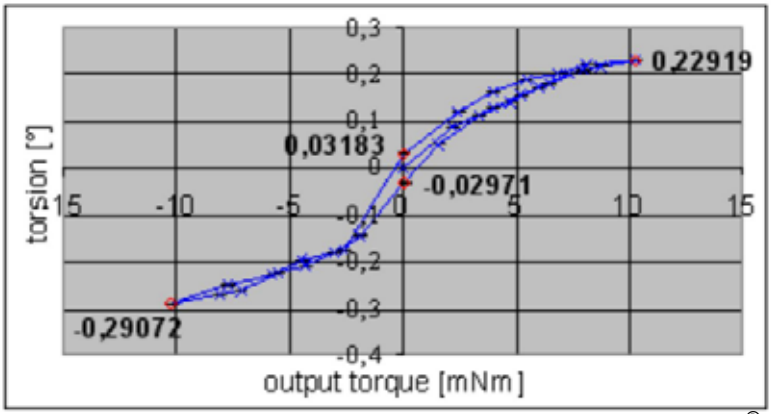

Figure 4.5: Hysteresis of the Micro Harmonic Drive®

The high efficiency and precise transmission behaviour of the zero backlash Micro Harmonic Drive® is shown clearly by the narrow hysteresis curve and the resultant low hysteresis losses of less than 0,1° (see Figure 4.5). The most important data and measured values of the realized Micro Harmonic Drive® gears are listed in Table 4.1.

Table 4.1: Key performance data for MHD gearboxes

Gearbox size		MHD 8		MHD 10		
Reduction ratio		160	500	160	500	1000
Peak torque	[mNm]	14	20	24	36	48
Rated torque	[mNm]	7	10	12	18	24
Repeatability	[arcsec]	10	10	10	10	10
Outer diameter	[mm]	8	8	10	10	10
Weight (with input shaft)	[g]	3.5	3.5	5.7	5.7	5.7

Due to its properties, especially its high repeatability and its lost motion of less than 10 minutes the Micro Harmonic Drive® is ideally suited for applications in high precision micro positioning drive systems.

4.4. Advantages of 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 (Mean Time Between Failure) 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 Figure 4.2) 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 (-160° C - +150° C). It can also be applied in a vacuum [12], 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.

5. Direct LIG: the production process of the Micro Harmonic Drive® gear

The manufacturing of the tiny structural dimensions of the gear wheels of the Micro Harmonic Drive® gear is carried out by means of photolithographic processes. In order to be able to keep tolerances in the sub-micrometer range and also to exploit the properties of metallic gear wheels the "Direct LIG" process is used. The Direct LIG process is based upon the LIGA process [13] and includes the two steps Lithography and Electroplating (see Figure 5.1).