MICRO ACTUATORS FOR PRECISE POSITIONING APPLICATIONS IN A VACUUM

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Abstract:
The Micro Harmonic Drive® gear is now established in the precision machine market as an ideal solution for precise positioning applications. This gear is manufactured using a modified LIGA process, called Direct-LIG. This allows the cost-effective production of extremely precise metallic gear components. With a diameter of 10 mm or less and with a tooth module of 34 μm or less the Micro Harmonic Drive® is the world's smallest back-lash-free gear. It's excellent repeatability of less than 10 seconds of arc is the basis for a variety of applications for machines in the semi-conductor industry, optical devices and medical equipment.

Recently there is increasing demand for micro gears for applications in a vacuum. In the fields of semiconductor manufacturing, pharmaceuticals manufacturing and materials research there is a trend to place various process steps or analysis tasks into a high or ultra-high vacuum environment. This presents new and difficult problems to overcome for manufacturers of gears or actuators. To enable these products to be used in a vacuum environment special or dry lubricants must be applied and also special mechanical design modifications must be made. Micromotion GmbH, the manufacturer of the Micro Harmonic Drive®, has undertaken a development project involving tribological coatings to allow the use of this gear in such applications. In this paper we will present the various steps necessary to allow the use of the gear in a vacuum and will also describe an application in a micro-polarimeter for use in synchrotron research.

Keywords: Micro-gears, Micro-actuators, Micropositioning, Electro-mechanical actuator, Vacuum

1. Introduction

Vacuum technology is an increasingly important field, both in technological and commercial terms. This enabling technology is essential for almost all new products, production processes and research activities in the fields of semiconductor manufacturing, pharmaceutical production and space exploration. A clean environment, free from particles and with closely controlled pressure, is essential for an increasingly wide range of modern production processes. Only in such an environment can particular processes be executed, or products with the required quality be produced.

Applications in a vacuum environment are a particular challenge for motion control components. Special attention must be paid to the selection of materials, selection of lubricants and to methods of energy transfer. The precise and reliable movement of objects in a vacuum is only possible with specially developed mechanical and electrical power transmission components. This paper describes an innovative solution from the field of micro-systems-technology, which is opening up new opportunities for precise positioning tasks in a vacuum.

The advantages of a vacuum environment are being increasingly recognized for a wide range of modern manufacturing and measurement processes. These processes often involve the precise manipulation of a workpiece, tool or probe within a clean environment. Given that humans are a major source of contaminants there is also an additional trend to the complete automation of such processes. Last, but not least, the motion control components necessary for these precise movements are themselves increasingly located in the vacuum environment. This avoids the need for expensive and often imprecise mechanical feed-throughs to convey mechanical movements into the vacuum environment from outside.

The logical consequence is that the demand for vacuum-compatible motion control components is growing quickly. This demand is growing particularly strongly for miniaturised power transmission components, because the workpieces, tools or probes to be positioned are themselves often very small in scale.

Developing motion control components with small dimensions, in the range of a few millimetres, is an additional challenge for the development of vacuum-compatible gears and actuators. The materials used must be chemically resistant, Have a low outgassing rate, exhibit a low vapour pressure and also exhibit acceptable thermal expansion characteristics. The lubricants and adhesives used must also withstand the demands of the vacuum environment [1]. These complex requirements are surely the main reason that miniaturised vacuum-compatible gears and electro-mechanical actuators have not been readily available in the past.

The designers of vacuum equipment have therefore been forced into a compromise. They have either had to mount the power transmission components outside the vacuum and use mechanical feedthroughs to bring movements into the vacuum, or have been forced to use "unconventional" motion control components. These components, such as piezo-actuators, are either very expensive, difficult to control or have poor positioning performance characteristics.

The demand for miniaturised electro-mechanical motion control components, that are highly precise, easy to control and affordable is therefore very large.

2. Micro Harmonic Drive Gears and Actuators

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. 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 [2] **(Fig. 1)**.

Fig. 1 *Micro Harmonic Drive gearbox and actuator*

This gear was developed by Micromotion GmbH in Mainz, in co-operation with the Institute for Microtechnology, also located in Mainz in Rhineland-Palatinate, Germany. 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 **(Fig. 2).**

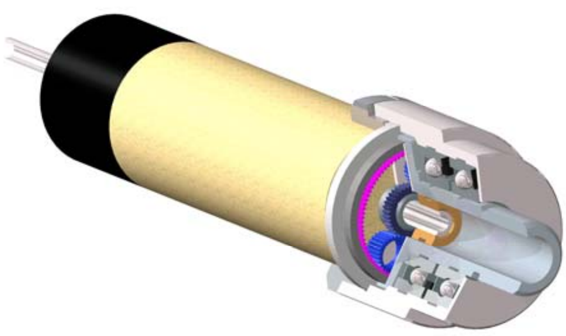

Fig. 2 *World's smallest zero backlash actuator (diameter 8mm, length 31,3 mm)*

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 micro-motors 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 planet wheels are hollow and elastically deformable, with the result that backlash can be eliminated by gear pre-loading in the planetary gear stage.

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 order to allow easy integration in a wide range of different applications the component set is mounted inside a micro-gearbox of the MHD series, which is available in two sizes, either with an input shaft or for direct coupling to commonly available micro-motors from Arsape, Escap, Faulhaber, Maxon, Mymotors, Myonics, Phytron etc. [4].

This solution 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/s^2 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 micro-gears. This is mainly the result of the far lower number of parts, compared to other gears. A planetary micro-gear 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). As will be described subsequently it can also be applied in a vacuum, using grease, oil or dry lubrication, depending on the specific requirements of the application.

Gearbox size		**MHD 8**		**MHD 10**		
Reduction ratio		160	500	160	500	1000
Peak torque	[mNm]	6	16	10	26	40
Rated torque	[mNm]	3	8	5	13	20
Repeatability	[arcsec]	10	10	10	10	10
Outer diameter	[mm]	8	8	10	10	10
Weight	[g]	3.5	3.5	5.7	5.7	5.7

Table 1 Key performance data

3. Modifications for Vacuum Applications

As mentioned above, a number of modifications must still be made, in order to allow reliable operation in a high vacuum or ultra high vacuum environment [4]. Even though the standard gearbox features high quality materials and a high level of corrosion resistance there are still some parts that must be modified or replaced. The standard output bearings are replaced by dry lubricated bearings with specially coated raceways. Depending on the level of vacuum the gear itself is either lubricated with a special vacuum-compatible grease, or is provided with dry lubrication supported by a special galvanically applied tribilogical coating of the gear teeth **(Fig. 3).** A further detail design modification concerns the adhesives used to fix the individual gear components. Here, too, a special UHV-compatible adhesive is used. All these modifications have been tested successfully at pressures as low as 10^{-12} bar.

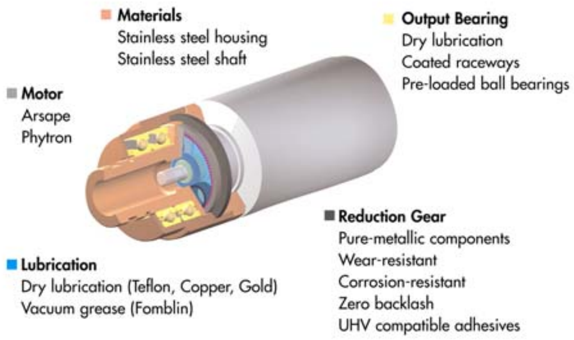

Fig. 3 *Special modifications for vacuum applications*

4. Application Example

This innovative micro-gear is already being used in practical vacuum applications. A good example is a new micro-polarimeter developed at BESSY in Berlin **(Fig. 4).** This high precision, high vacuum compatible (UHV) polarimeter is a multipurpose instrument which can be used as a self-calibrating polarisation detector for linearly and circularly polarised UV- and soft X-ray light. It can also be used for the characterisation of either reflection or transmission properties (reflectometer) or polarising and phase retarding properties (ellipsometer) of any optical element. This device is also used to identify the concentration of elements featured in thin magnetic coatings using, for example, the magneto-optical Kerr effect in the soft X-ray region. **Fig. 4** shows the complete sub-assembly comprising two vacuum-compatible micro-gearboxes, driven by a single vacuum-compatible motor. One micro-gearbox is used to accurately position the deflection mirror, while the other is used to position the detector. The deflection angles of the mirror and detector have a fixed relationship, and this is achieved by using two spur gear stages with different ratios as input stages for the two micro-gearboxes. The spur gears are mounted on the input side of the backlash-free gears The high reduction ratio of the Micro Harmonic Drive® gear has the result that the backlash in the spur gear stage has no noticeable effect on the positioning accuracy of the mirror or detector. A repeatability of +/- 20 seconds of arc is achieved for both rotational axes. Importantly, this is achieved with open loop positioning control. The motor used is a vacuum-compatible stepping motor from Phytron and no additional position measurement system is required.

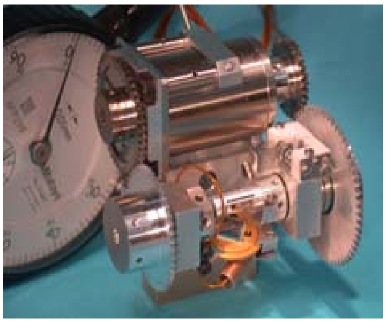

Fig. 4 *Micro-Polarimeter (Source: BESSY, Berlin)*

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