PRECISION POSITIONING DOWN TO SINGLE NANOMETRES BASED ON MICRO HARMONIC DRIVE SYSTEMS

Andreas Staiger and Reinhard Degen

Micromotion GmbH, An der Fahrt 13, 55124 Mainz, Germany
info@micromotion-gmbh.de

Abstract At present the Micro Harmonic Drive is the world's smallest backlash-free micro gear. Its favourable properties such as high repeatability, high torque capacity, low mass of inertia and high degree of efficiency are proved applied in different applications for semiconductor manufacturing, measuring machines, aerospace and other industries. However for high precise assembly applications often linear adjustments of a few nanometres are required. The common solution for positioning in the nanometres range is the use of piezoelectric effect actuators. The drawbacks are the need for a closed loop control system, overshooting during positioning, local wear, short travel ranges and loss of position without power supply. To overcome these obstacles the advantages of the Micro Harmonic Drive are exploited together with a stepper motor, an eccentric drive and monolithic flexure hinges are combined in a compact unit, called Nanostage. With this setup a travel range of 40 microns and a resolution < 3 nm is achieved. The single sided and double sided repeatability was measured in an open loop control system with < 5 nm and < 10 nm respectively.

1 Requirements for micro actuators in positioning systems

For products consisting of micro parts the assembly can add up to 80 % of the production costs [1]. For the automation of the assembly processes specially designed machines are necessary to handle micro parts. Typically movements with several degrees of freedom realised by motors, gears and lead screws are necessary. As a result of using conventional drive technology the assembly machines need a multiple of space against the handled parts. To increase the accuracy and reduce the cycle times the size of the precision assembly machines had to be reduced to the range of the micro parts. Therefore fast, precise and reliable micro actuators for rotational as well as for linear movements are needed. Moreover further integration of functionalities like vacuum feed-throughs or sensors are needed [2]. The development of micro motors [3, 4] and backlash-free micro gears [5] allow densely packed micro-electro-mechanical systems for innovative positioning applications [6]. The advantages of such micro actuators are their low mass of inertia, small footprints and often long tools that amplify inaccuracies are dispensable. Due to the low mass of inertia which accounts for high acceleration the power dissipation is reduced and therefore effects of changing temperatures ranges on the accuracy are almost negligible. If the assembly has to be done under special environmental conditions, smaller footprints of the assembly machines led to lower costs.

Fig. 1 Micro Harmonic Drive and servo actuator

The key elements of such micro systems are compact sized gears like the backlash-free Micro Harmonic Drive (Fig. 1). This gear principle provides a unique combination of precision, torque capacity, power density, high degree of efficiency, low mass of inertia, hollow shaft, robustness and a wide range of reduction ratios within the same dimensions and the same number of gears. They have proved their ability for assembly processes for years in semiconductor and other assembly machines.

For high precision adjustment applications the advantages of the micro gears are transferred over in linear movements. For travel ranges between 0.5 mm and 2 mm an eccentric drive consisting of a backlash-free eccentric, a micro harmonic drive and a stepper motor are applied. With such a system a resolution of 0.15 µm can be achieved (Table 1).

Table 1. Technical data of eccentric drive

	Unit	**Value**
Cross section	mm	10
Length	mm	43.5
Travel range	mm	2
Linear speed	mm/s	2
Force	N	12
Resolution (half step)	µm	0.15
Repeatability	µm	+/- 1
Mass	g	10

2 The Nanostage

For some adjustments, such as movements of optical lenses, accuracy in the single nanometre range is requested. To realise positioning units for the single nanometre range with conventional drive technology, new adaptation mechanisms are necessary to cope with requests regarding stiffness, guidance and controllability [7-9].

2.1 Boundary conditions for the Nanostage

Current systems with a resolution in the nanometre range are mostly based on piezoelectric effect actuators. The drawbacks of such systems are:

- Loss of position if power supply is interrupted
- Local wear, especially by inch-worm drives
- Need for a closed loop control system
- Need for position measuring system
- Overshooting during positioning
- Short travel ranges compared to the actuator size

The aim for the development of a new positioning mechanism was the use of common control systems within the resolution of single nanometres. Therefore a backlash-free eccentric drive (Table 1) is combined with monolithic flexure hinges (Fig. 2). Because of the stepper motor, only a common open loop stepper control unit is necessary. Moreover by the use of a high reduction ratio gear set a high resolution is achieved.

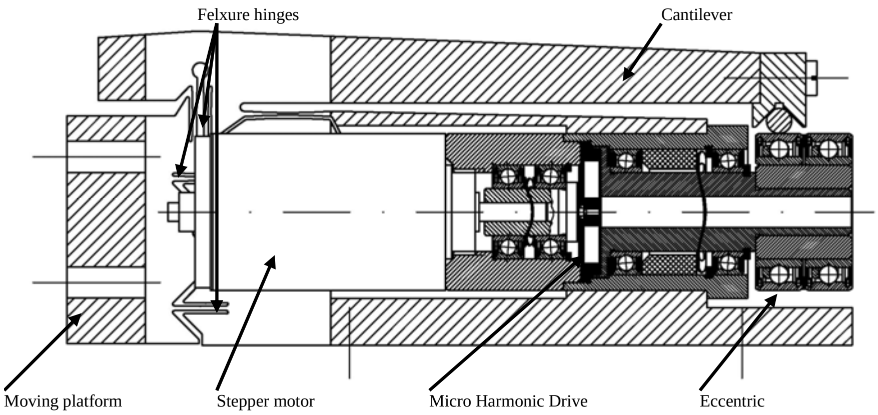

Fig. 2. The Nanostage. Conventional drive technology for high precise positioning

The flexure hinges provide on the one hand the guiding system and on the other hand an additional reduction ratio. Through the monolithic manufacturing, influences on the accuracy caused by assembling such as asymmetric stress or unbalanced tightened screws are avoided. Another important influence on the accuracy is the quality of the output shaft bearings. True running deviations caused by manufacturing, assembly and the bearings itself are visible in the transmission accuracy of the system. Therefore the true running requirements of these parts are in the single micrometre range. As a result of this requirement the bearing carriers have to be manufactured in one chucking and the ball bearings are preloaded axial so that the balls are running on the high surface finished inner and outer rings of the bearings.

2.2 Structure synthesis

The kinematic train of the Nanostage consists of the following components:

- Stepper motor with 20 full steps per revolution
- Micro Harmonic Drive with ratio 1000 : 1
- 1 mm eccentric
- Flexure hinges with ratio 50 : 1

The aim of the design was a couple hinge guiding to avoid the more complex manufacturing of a four-point spring guidance. It was designed as follows:

- Material AL7022
- Length of spring: 5.37 mm
- Width of spring: 4 mm
- Minimum thickness: 0.2 mm
- End thickness: 0.266 mm
- Allowed linear deformation at 2.2 N: 17 µm
- Allowed angular deformation at 2.8 Nmm/rad: 16.2 mrad

This led to a length contraction of just 0.04 µm with allowed linear deformation. Due to better manufacturing capabilities and the sufficient guidance accuracy resulting from the spring contraction, the concept of a four-point spring guidance was chosen. It is regarded as the best solution both technically and economically. Two more points had to be regarded in the design of the flexure hinge. First, at z-accelerations the cantilever could lift-off. This is prevented by a flexure pre-load of the eccentric bearings. Second, at acceleration across the moving direction, the cantilever could oscillate so that the eccentric bearings could be affected. An additional leaf spring between cantilever and body for prevention is included.
This led to the following structure of the flexure hinge:

- 2 x 2 guidance springs induce the intended short linear movements.
- 2 cantilever springs to induce an additional ratio of 50 : 1. They are deformed angular (+/- 16 mrad). For this hinge no requirements regarding the length constancy or linear deformation exist.
- 1 leaf spring to guide the cantilever. It is 70 µm linear and +/- 16 mrad angular deformed.

2.3 Manufacturing of the flexure hinges

The body is manufactured of Al7022 (Fig. 3). Short and therefore thin springs with high tension load are preferred to reduce cutting time in the eroding process. The cutting width for the flexure hinges could be to a large extent optimised to process parameters. The accuracy of the outline of the five hinges that are remaining as bars in the body is critical. Therefore the tolerance and the roughness have only to be minimized in these areas. For the other parts the cutting speed could be higher.

Fig. 3. The Nanostage. The moving platform contains four M2 threads and two 2H7 fits. Size: 20 x 20 x 50 mm³

3 Measurements

To measure the resolution of the Nanostage a capacity sensor with a resolution of 5 nm was utilized. Because of the A/D converter used for the analysis the resolution was reduced to 10 nm. The measured resolution is 10 nm, that is equivalent to one digit. As the resolution is limited by the used measuring system it is assumed that the resolution of the Nanostage is below 10 nm. This has to be verified with a laser interferometer.

Fig. 4 shows the Fast Fourier Transformation of the transfer function. The fundamental wave shows the maximum travel range. The first harmonic wave shows the deviation from an ideal sinus caused by nonlinearities in the guiding and the flexure springs. The higher harmonics are caused by concentricity faults of the ball bearings. The highest influence on the position accuracy is the slightly nonlinear ratio of the cantilever, followed by the nonlinearities of the flexure hinges and the concentricity faults of the ball bearings caused by the quality of the surface finishing and assembly.

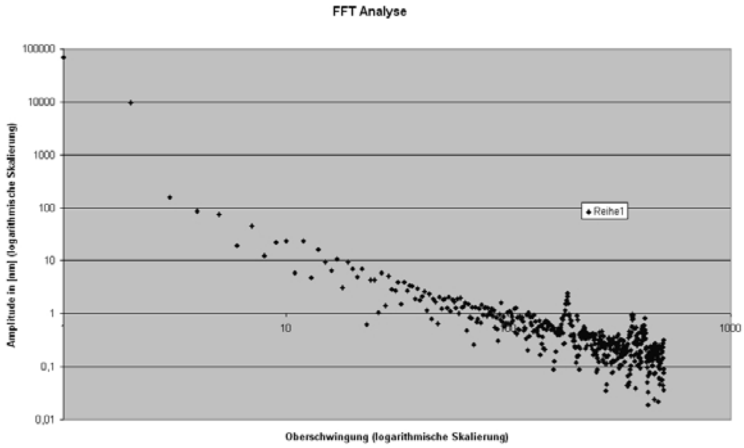

Fig. 4. FFT-analysis of one cycle to identify failure influences. Ordinate: amplitude in nm, logarithmic. Abscissa: Overshooting, logarithmic.

4 Conclusion

The Nanostage provides a compact unit for positioning in the nanometre range by using conventional micro drive technology. Consequently the advantages of an open-loop stepper motor control unit and hold of the position without power supply can now be utilized in nanometre positioning and assembly systems (Table 2).

Table 2. Technical data of the Nanostage

	Unit	**Value**
Dimensions	mm	20x20x50
Travel range	µm	40
Resolution (half step)	nm	<10
Linear speed	µm/s	2
Force	N	12
Mass	g	0.15

The theoretical resolution of < 3 nm and the repeatability have to be verified with a laser interferometer.

References

1. J. Hesselbach and A. Raatz, mikroPRO – Untersuchung zum international Stand der Mikroproduktionstechnik (Vulkan Verlag, Essen, 2002).
2. R. Degen and R. Slatter, High Speed And Low Weight Micro Actuators For High Precision Assembly Applications, Proceedings of IPAS, Bad Gastein (2006).
3. C. Thürigen, W. Ehrfeld, B. Hagemann, H. Lehr and F. Michel, Development, fabrication and testing of a multiple-stage micro gear system, (Proceedings of Tribology issues and opportunities in MEMS, Columbus (OH), (Kluwer Academic Publishers, Dordrecht, 1998) pp. 397-402.
4. S. Kleen, W. Ehrfeld, F. Michel, M. Niehaus and H.-D. Stölting, Ultraflache Motoren im Pfennigformat, F&M, Vol. 108, No. 4, (Carl Hanser Verlag, München, 2002).
5. R. Degen and R. Slatter, Hollow shaft micro servo actuators realized with the Micro Harmonic Drive, Proceedings of Actuator, Bremen (2002).
6. R. Slatter, R. Degen and A. Burisch, Micro Mechatronic Actuators for Desktop Factory Applications, Proceedings of the Joint Conf. on Robotics, München (2006).
7. S.T. Smith and D.G. Chetwynd, Foundations of Ultraprecision Mechanism Design (Taylor & Francis Books Ltd, London, 1998).
8. A.H. Slocum, Precision Machine Design (Society of Manufacturing Engineers, Dearborn (MI), 1992).