Linearization of an Open-loop Nano Fast Tool Servo

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Abstract

Fast Tool Servo assisted turning processes have become a popular way to generate freeform surfaces and microstructures. For machining submicron diffractive structures a precise positioning of the tool actuator is important. To achieve accuracy within nanometer range an efficient system design is fundamental. This paper presents the system design of two piezoelectric nano Fast Tool Servos (nFTS) with strokes of less than 500 nm to achieve a high linearity.

1 Introduction

Many optical systems use compact optical elements with complex functionalities. Especially in micro-optics the application of refractive lenses has shifted to diffractive optical elements (DOE) in order to satisfy the requirements of miniaturized and compact designs [1]. A common way to fabricate freeform surfaces and microstructures is the combination of a turning process with a fast tool servo (FTS) [2, 3]. However, existing FTS do not fulfil the requirements regarding stroke, frequency and positioning accuracy in order to fabricate high-resolution DOEs. Commercially available solutions such as the Precitech FTS™ 70 feature a suitable stroke and positioning accuracy but the maximum operating frequency of 700 Hz is insufficient. Therefore, two differently designed nano Fast Tool Servos (nFTS) have been developed, which are capable of modulating the depth of cut within nanometer range at frequencies up to 5 kHz and 10 kHz, respectively. These enable the generation of individual structure elements within the tool path with varying nanometer height levels. The precise positioning of these structure elements and their individual height levels are essential for the optical functionality of the surface. A suitable actuator design to guarantee the required precision is based on piezoelectric ceramics. With the developed actuators a continuous adjustment of the actuator position is possible [4]. However, it is necessary to design the system efficiently to minimize hysteresis and maximize the linearity.

2 Machining process

The process for machining diffractive microstructures is a face turning process combined with a nFTS for a variation of the depth of cut within nanometer range. A diamond knife tool is used to generate a blaze-structure, which serves as diffraction grating. The blaze-structure is a suitable geometry regarding optical and machining requirements. The nFTS control system and data processing sequence for fabricating discontinuous structures are shown in Fig. 1.

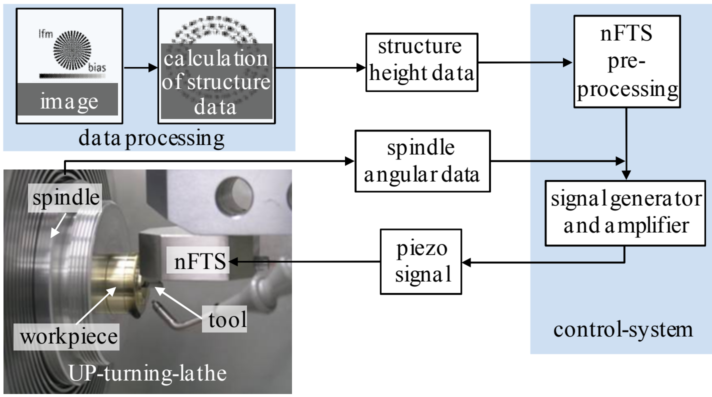

Figure 1: nFTS control system and data processing sequence

Starting point is the data processing, to calculate the structure height data of the intended hologram. The Cartesian coordinates of the original image have to be converted into polar coordinates, in order to meet the requirements of the turning process including spiral tool trajectory, feed and tool geometry. The resulting structure height data serve as input for the nFTS control system. Corresponding to the structure height data control voltages are generated to adjust the nFTS position. In order to achieve a precise positioning in cutting direction the positioning signal of the main spindle is used to trigger the nFTS movement. To simplify the system an open-loop control is used, which requires an efficient design of the nFTS.

3 Design and linearization of the nFTS

The specification of the nFTS design is based on the final application. In the case modulating the depth of cut of a turning process to generate a diffraction grating, a short stroke and high linearity are required. The linearity is influenced by hysteresis of the piezoelectric ceramic. Since hysteresis correlates with the nominal stroke, a reduction of the stroke reduces the hysteresis. Furthermore, the piezoelectric material is crucial. The used material shows a near zero hysteresis and negligible heat dissipation, and therefore, deviations of the nominal stroke are minimized.

To assess the performance of the designed nFTS, a plane mirror interferometer was used. Measuring the current actuator positions after applying defined control voltages delivered the correlation of stroke per voltage. The measured correlation was verified in cutting experiments in order to assess the performance during the cutting process. The machined test structures consist of sectors with defined height levels from 0 to 500 nm. The depth of cut was increased in steps of 50 nm. Atomic force microscopy (AFM) was used to measure the precision of the height steps. For each height step the positioning accuracy for increasing and decreasing the depth of cut was assessed. Fig. 2 presents the results of the test structure, which shows a maximum deviation of the target height of 10 nm.

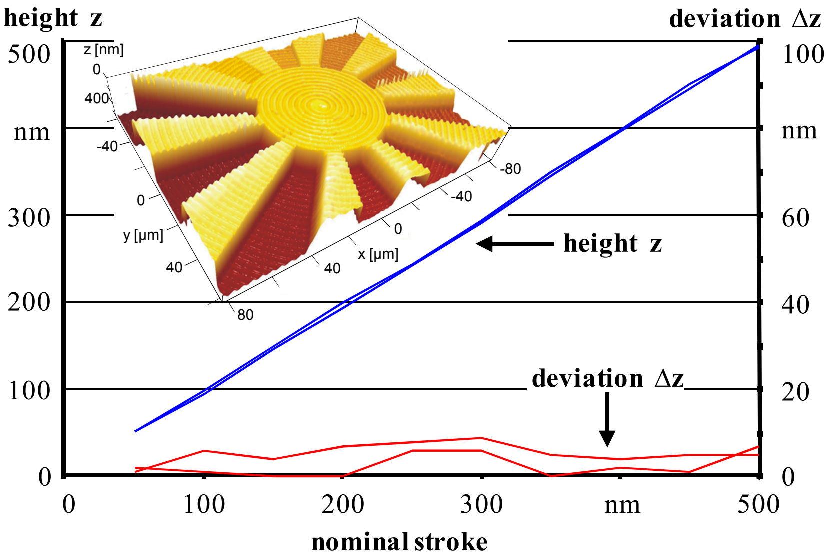

Figure 2: assessment of nFTS performance by measurement of test structure

Further improvement of the linearity was achieved by developing an advanced nFTS system. The second actuator version, nFTS#2, was developed to reduce the remaining deviations of the nominal stroke, and thus, to further improve the machining accuracy. The piezo stack size was reduced, which decreased the stroke to 350 nm.

Moreover, the geometry of the piezo ceramic was extended. By choosing a larger cross section of the piezo ceramic, the stiffness of the actuator in the direction of movement was improved. The reduced stroke and higher stiffness also increased the resonant frequency, which allows to operate the nFTS#2 at higher frequencies of up to 10 kHz. Overall, the modifications reduced deviations of the nominal stroke to less than 4 nm.

4 Summary

The design and linearization of nano Fast Tool Servos (nFTS) for machining discontinuous microstructures were introduced. To achieve a precise positioning of the tool actuator, an efficient system design is fundamental. Based on piezoelectric ceramics two nFTS systems were designed. The actuators are operated in an open-loop mode, which is possible due to low deviations of the nominal stroke. The high accuracy was achieved by choosing a short stroke of less than 500 nm and a specific type of piezo ceramic. The linearity was assessed by laser interferometer measurements and cutting experiments, which delivered the correlation between stroke and control voltage. System design and adaptation of the nFTS control reduced deviations of the nominal stroke to less than 10 nm.

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References:

[1] Bruzzone, A.A.G., Costa, H.L., Lonardo, P.M., Lucca, D.A.: Advances in Engineered Surfaces for Functional Performance. Annals of the CIRP, Vol. 57/2/2008: pp. 750-769.

[2] Weck, M., Oezmeral, H., Mehlkopp, K., Terwei, T.: A New Hybrid Concept for a Long Stroke Fast Tool Servo System. Proceedings of ASPE 1995Annual Meeting, 1995: pp. 211-214.

[3] Lu, X., Trumper, D.L.: Ultrafast Tool Servos for Diamond Turning, Annals of the CIRP, Vol. 54/1/2005: pp. 383-388.

[4] Lünemann, B.; Brinksmeier, E. et al.: Open-loop nanometerstroke Fast Tool Servo system for the generation of diffractive optical microstructures. Proceedings of the Actuator 2008 conference, Bremen, 2008.