Analysis of Control and Servo Drive Systems for the Application in Ultra Precision Machining

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Abstract

The mechanical design of ultra precision machine tools is very well experienced today. Detailed investigations on axes design, bearings and drives as well as overall machine concepts have build a broad basis for designing very robust and accurate state of the art machine tools. Enhancements to further increase the achievable form accuracy and surface quality and at the same time decrease cycle times and error sensitivity can only be accomplished by innovative control and drive systems, that are concurrently offering additional possibilities of automation, process integration, data acquisition and processing as well as computerized quality management strategies. In contrast to mechanical machine design, control and servo drive systems for ultra-precision machining and their interactional behavior within a complex machine setup have not been sufficiently analyzed yet. At the Fraunhofer IPT a test bench has been developed to analyze machine controls, servo drives and sensor systems with regard to an evaluation of capabilities of their application in an ultra precision lathe. This paper presents the test bench setup as well as first measurement results regarding the interpolation of setpoints in CNC machine controls as well as digital servo drives.

1 Analysis of closed control loops for ultra precision machining

Analyzing closed loop control systems for highly dynamic and high bandwidth axes requires both, a detailed examination of each individual component included in the control loop, and at the same time a close investigation of the system as a whole. Focusing on hardware structures, software modules as well as on data processing, an overall statement concerning all aspects of modern closed loop control systems can be elaborated. Various parameters of CNC machine controls such as interpolation parameters, programming resolution or cycle times strongly influence the accuracy and dynamics of high precision axes. Additionally, the performance of servo drives depends on several design and tuning aspects such as the drive structure – analog or digital, the control strategy – PID-control or cascade circuits, or possibilities of decentralization – closing the loop in the drive or in a overlaying pc-based control. Furthermore, sensors in the feedback path are essential components of the control loop limiting the accuracy and dynamics of precise machine axes. All of these components and parameters have to be taken into consideration to optimize the control loop for highly dynamic and high bandwidth axes (Figure 1 left).

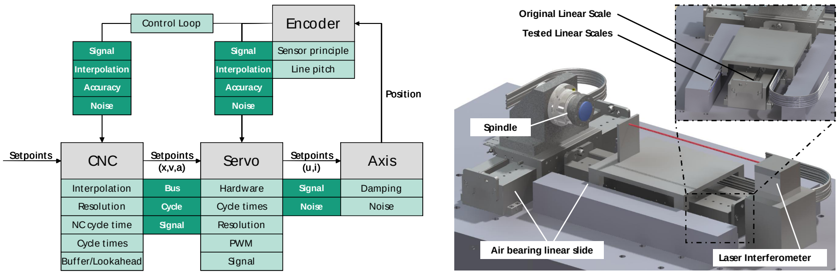

Figure 1: Schematic block diagram of control loop/ test bench setup

To analyze all components applied in closed control loops and to simultaneously identify mutual disturbances and limitations within the whole system, a modular test bench has been set up consisting of two air bearing linear slides, an air bearing spindle, various feedback sensors and a modular switch cabinet enabling an easy exchange of controls and drives (Figure 1 right). The arrangement was chosen like an ultra-precision lathe to finally verify the measured results by turning optical components and comparing the surface quality and contour accuracy achieved with different combinations of controls, drives, feedback sensors and data signals.

2 Influence of the sampling point density on CNC interpolation

Setpoint generation at a high frequency is often required for the machining of ultra precise components. Fast Tool turning of lens arrays as one application example depends on the provision of setpoints for the Fast Tool at a frequency of 20 kHz. To provide the Fast Tool axis with such setpoint data two alternatives are possible: First, setpoints can be generated by the NC kernel of the machine control, which has the drawback of depending on the NC interpolation and cycle time. Second, an external setpoint computer can be implemented, enabling the more accurate calculation of setpoints from analytical surface descriptions, but has the drawbacks of additional communication structures and a higher error sensitivity. With respect to advantages of an integrated control for all axes, generating setpoints within the machine control is the more feasible approach, but on the other hand strongly depends on the number of sampling points and the calculation time. To analyze this influence on the quality of NC interpolation a test surface described by the Franke function [1] was applied to a Fast Tool axes under variation of the sampling point density. Figure 2 shows an excerpt of the interpolated tool path (left) and the resulting error (right) of the Fast Tool position for different quantities of sampling points.

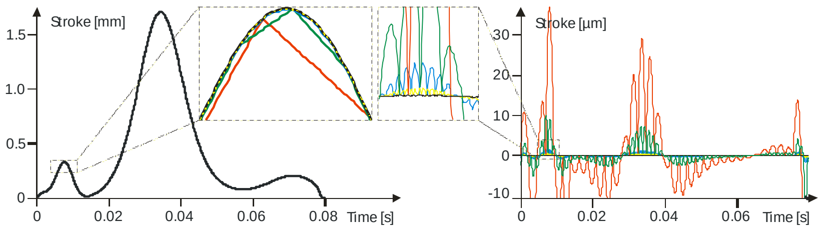

Figure 2: Interpolated path/ error of a tool under variation of sampling point density

3 Digital servo drives

As aerostatic lightweight axis have the disadvantage of low mechanical damping, linear amplifiers with analog position controls are still used for the control of ultra precision axes to avoid a loss of axis stiffness and an insufficient damping of system noise. Modern switching amplifiers afford PWM clocks over 100 kHz for 3-phase driven motors and over 500 kHz for 1-phase driven motors like voice coils. Therefore, they can reach the signal quality of analog amplifiers, but additionally allow for higher flexibility, higher efficiency ($\eta > 90\%$), a compact circuit layout and smaller heat sinks as well as a higher current resolution and a higher control bandwidth. FPGA-based circuits can extremely reduce system latency caused by the digital control system loop and the I/O conversion [2, 3]. Using FPGA-based position control loops, the axis dynamic can be raised over 50% compared to standard micro controllers [3]. Figure 3 shows a step response measurement conducted at the aforementioned test bench. The position noise could be reduced to 3 nm std. by using an FPGA-based control circuit and digital power amplifiers. These first results show that digital servo drives are capable of reaching the rate of analog control circuits.

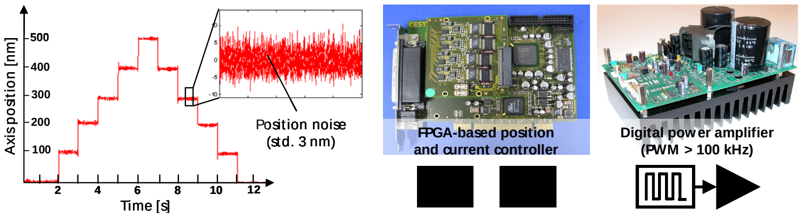

Figure 3: Step response measurement of an FPGA-controlled aerostatic axis

4 Conclusion and Outlook

At the Fraunhofer IPT a test bench has been set up to analyze control and servo drive systems for the application in ultra precision machining. First results show a strong influence of the sampling point density on the quality of NC interpolation and prove that FPGA-based digital servo drives can reach the performance of analog amplifiers. Future investigations will focus on optimizing the signal path of setpoint generation for highly dynamic axes as well as on finding ideal parameters for digital servo drives to further enhance the accuracy of aerostatic machine axes.

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