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Detection of tool deflection in milling by a sensory axis slide for machine tools

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ABSTRACT

Previous publications regarding the project Gentelligent Components for Machine Tools of the Collaborative Research Center 653 presented the design of a new sensory *z*-slide for a 5-axis machining center. Equipped with several strain sensors, the new slide is able to feel the machining process by measuring the process forces and vibrations. Here, a challenge is the detection of mechanical strains in the slide without degrading its high global stiffness. The application of micro strain gages in small notches on the slide represents a promising approach for the improvement of the sensitivity as well as the integration of sensors into the slide. This paper presents the utilization of the sensing axis-slide in a manufacturing environment. For this purpose, a first prototype of the slide is build and integrated into a milling center DMG HSC 55 linear. In this test machine, the dynamic characteristics of the integrated slide are identified with frequency response function measurements. Based on force measurements with a dynamometer, force calibration matrices are computed to calculate the forces in the machine coordinate system at the tool center point from the measured strain signals during milling processes. The force sensing with the slide allows furthermore the identification of tool characteristics such as the static tool stiffness. This parameter is estimated from the ratio of the measured contact forces and the set collision distance when moving the tool smoothly into the work piece. The known tool stiffness enables the detection of the static tool deflection from the force signals during a milling process. To compare the detected tool deflection with the real tool deflection, reference measurements on the work piece are performed using a perthometer. For further monitoring applications of the tool deflection in more complex 2.5D milling an approach to transform the measured forces from the stationary machine coordinate system into the moving tool coordinate system is presented.

1. Introduction

Recent improvements in production engineering lead to constantly increasing flexibility, productivity and a higher level of automation. This development results in generally higher demands on machine components and process monitoring strategies. The main aim of process monitoring is the early detection of process failures such as tool wear, tool breakage, and chatter, in order to reduce ultimately the resulting failure costs.

The process force is the most important size to describe a process during manufacturing. The first difficulty lies in the generation of signals, which correlate well with that force. To get such signals, sensors can be integrated in machine tool components. For instance incorporating sensors in the tool holder was achieved in [1], whereby the integration of the force sensor system led to a loss of stiffness and a sophisticated radio transmission of signals was needed. In [2,3] a sensing clamping system with piezo actuators was developed in order to reduce the vibration of workpieces during manufacturing. In [4,5] strain gages and acceleration sensors were combined into a sensor network and integrated in a sensory clamping system. In a further step, this clamping system was combined with an adaptronic spindle and allows a robust force-related process monitoring with high sensibility [6].

Within the collaborative research center CRC 653 [7], workpieces are manufactured using the "feeling" machine tool. This new kind of machines has the specific functionality to sense the vibrations and the forces which occur during machining. The feeling machine tool is realized by integrating sensory machine components [5,8] which are directly involved into the flux of force and closely located to the process. In milling, the *z*-axis-slide which carries the working spindle is suitable for the application. The load detection is realized through strain measurements on the structure. Machine components like the axis-slide are generally over designed with respect to their stiffness in order to achieve the

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requirements for high machining accuracy and process stability. Therefore, the strains in the structure are very low and can hence hardly be measured. A big challenge is thereby to achieve a high sensitivity of the component without lowering its stiffness. The provided process signals from the slide can be used in many applications, such as the optimization of machine components or the design of work tools, and represents a basic information source for process and condition monitoring systems.

2. Prototype

The determination of the process forces is achieved by measuring the mechanical strain in the structure of the *z*-slide. Due to the high stiffness of the *z*-slide, only minimal strains occur in the structure under machining forces. Hence the strain measurement under these conditions becomes difficult. Indeed, the strain signals from conventional strain gages in preliminary experiments showed a very low signal-to-noise ratio. A method to increase the signal amplitudes without increasing the signal noise is the local adjustment of the flux of force in the component structure [8]. Thereby, the adjusted flux of force leads to local increase in the mechanical strain. This is achieved by manufacturing of small notches in the structure of the *z*-slide. Because of the negligible dimensions of the notches compared to the *z*-slide, the change of the slide stiffness due to the notches lies in the range of 0.1% (Fig. 1). Their influence can be therefore ignored.

In order to detect the mechanical strain, miniature strain sensors have to be integrated into the small notch grounds. In the *z*-slide two different kinds of miniature strain gages which were developed within the CRC 653 are applied: the first kind includes laser structured strain gages (L-SG) which are directly sputtered on any 3D-surface and subsequently structured using a laser beam [9]. The second kind consists of micro strain gages which are based on flexible polymer substrate and can be applied only to flat surfaces (μ-SG) [10]. The strain gages are applied in the positions P1 to P4 shown in Fig. 2. These positions correspond to locations in the *z*-slide which exhibit the highest sensitivity to mechanical strain as calculated from FEM-simulations. All used strain gages

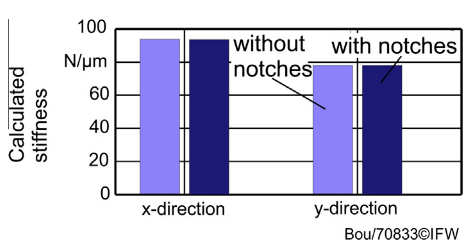

Fig. 1. Influence of the notches on the calculated slide stiffness.

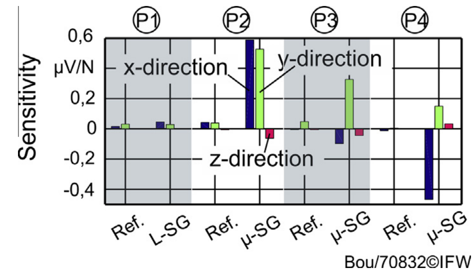

Fig. 3. Influence of the notches on the sensitivity to load.

are connected with electronic signal processing devices to compute and communicate the signals to the unit control. The prototype has been integrated into a milling center DMG HSC 55 linear.

Fig. 3 shows the sensitivity of the strain gages according to static forces at the TCP in the directions *x*, *y* and *z*. In general, the strain gages in notch (L-SG, μ-SG) show clearly a big increase in the sensitivity to load compared to conventional strain gages (Ref.) which are located very closely to the positions but not integrated in notches. This effect occurs stronger with the micro strain gages than with the laser-structured gages. In comparison to *x* and *y* directions, it seems that the *z*-slide is not sensitive to load in the *z* direction. This is caused due to the higher stiffness of the *z*-slide in this direction.

As the sensory slide is developed to be used especially during the milling process, its dynamic behavior regarding excitation frequency on the cutter tip is investigated.

3. Dynamic behavior

Fig. 4 presents the experimental set up to investigate the dynamic behavior of the integrated *z*-slide in the machine tool. To provide the excitation force, an electro dynamic shaker is used. The shaker is fixed on the clamping table and attached to the dummy tool through a quill. A force sensor is mounted to the tool side of the quill to measure the applied force. The *z*-slide is excited with a linear frequency sweep. As the maximal sampling frequency on the signal processing devices of the strain gages is currently limited to 500 Hz, the excitation frequency is increased only up to 200 Hz. From the strain and the force signals the frequency response function of the *z*-slide is computed. Fig. 4 presents on the right side the frequency responses with respect to the positions P1 to P4 defined in Fig. 2.

It shows that until 100 Hz the sensitivity of the strain gages is quite stable for the *x*- and *y*-direction. From 100 Hz to 150 Hz natural frequencies of the slide appear. The strain gages which are integrated in notches show again the effect of the notch on the signal improvement in comparison to the reference.

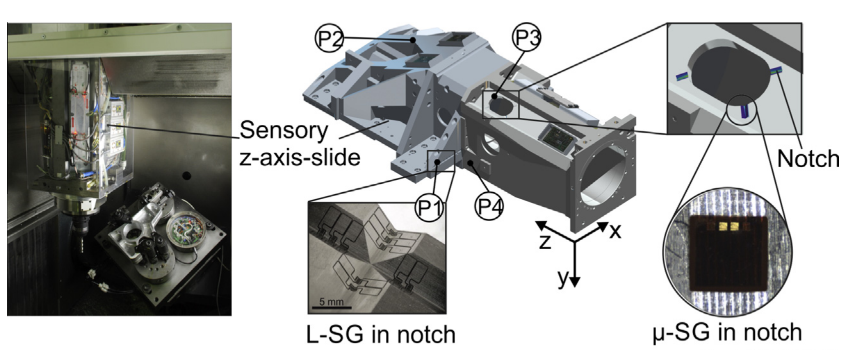

Fig. 2. Integrated sensory *z*-slide in the test machine tool.