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Process monitoring with a force sensitive axis-slide for machine tools

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Abstract

Previous publications regarding the project "Gentelligent Components for Machine Tools" 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 gauges 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 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 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 colliding 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. In order to compare the detected tool deflection with the real tool deflection, reference measurements on the work piece are performed using a perthometer.

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1. Introduction

Within the collaborative research center CRC 653 [1], work pieces 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 [2, 3] 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 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 therefore 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.
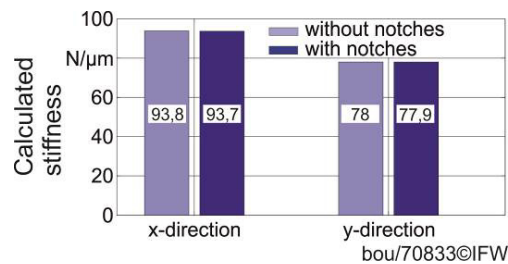
2. Prototype

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

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 gauges 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 [3]. 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.
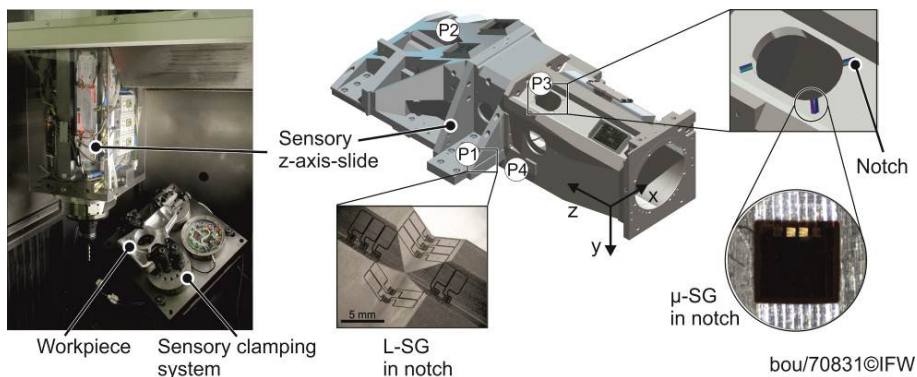

Fig. 2. Integrated sensory z-slide in the test machine tool.

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 gauges which were developed within the CRC 653 are applied: the first kind includes laser structured strain gauges (L-SG) which are directly sputtered on any 3D-surface and subsequently structured using a laser beam [4]. The second kind consists of micro strain gauges which are based on flexible polymer substrate and can be applied only to flat surfaces (μ-SG) [5]. These strain gauges 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 gauges 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.
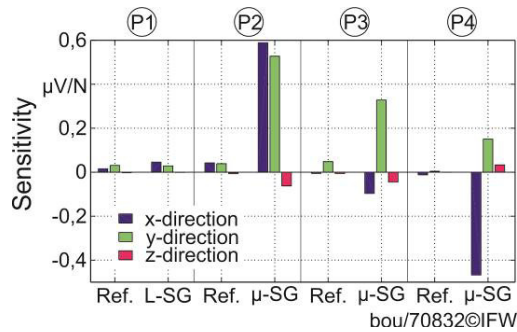

Fig. 3. Influence of the notches on the sensitivity to load.

Fig. 3 shows the sensitivity of the strain gauges according to static forces at the TCP in the directions x, y and z. In general, the strain gauges in notch (L-SG, μ-SG) show clearly a big increase in the sensitivity to load compared to conventional strain gauges (Ref.) which are located very closely to the positions but not integrated in notches. This effect occurs stronger with the micro strain gauges than with the laser-structured gauges. 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 behaviour regarding excitation frequency on the cutter tip is investigated.
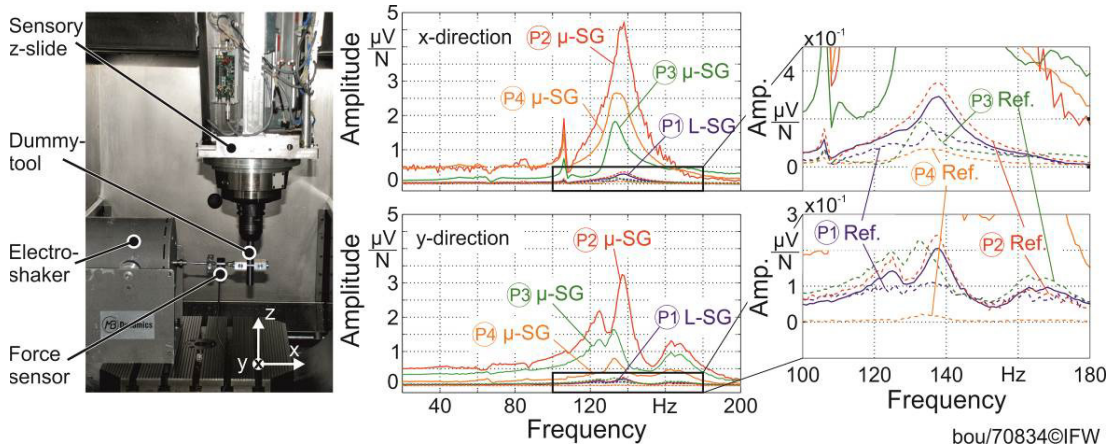
3. Dynamic behavior

Fig. 4. Test setup and frequency responses of the sensory z-slide.

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 gauges is currently limited to 500Hz, 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 gauges is quite stable for the x- and y- direction. From 100 Hz to 150 Hz natural frequencies of the slide appear. The strain gauges which are integrated in notches show again the effect of the notch on the signal improvement in comparison to the reference.

4. Calibration of the slide forces

The aim of the z-slide calibration is to determine mathematic matrices which are able to convert the signals of the strain gauges into load force signals. The calibration matrices are computed by a linear regression analysis using reference force signals and all strain signals of the z-slide. The low sensitivity of the slide in the z-direction impedes the force measurement in this direction. That is why the calibration neglects this force. The forces in the x- and y-directions can be detected accurately due to the high sensitivity to load of the strain gauges. Because each integrated strain gauges is sensitive for both directions, the force calibration depends on, how the load force is applied at the TCP. Two situations can be distinguished: the first situation arises during the milling process. Thereby, process forces in x- and y-directions are applied simultaneously. Each strain gauge provides a signal as response to the combined loads from both directions. In this case, the static calibrations of the x- and y- forces should be computed in parallel using the process forces. The second situation occurs by offline applications, where the slide is excited statically by forces in only one direction, either x- or y-direction, such as the stiffness measurement of the z-slide. Each strain gauge delivers a signal as response to a simple load. In this case, the slide calibration in x- and y-direction should be executed separately using statically applied forces at the TCP.
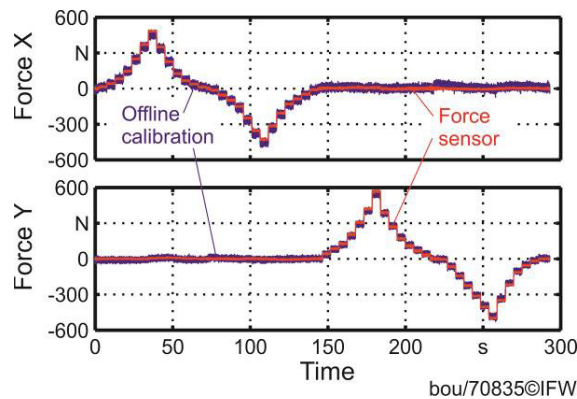

Fig. 5. Offline force calibration of the z-slide.

In the offline force calibration, the forces are applied on the TCP of the z-slide, first in x then in y direction. The reference force signals are measured by a conventional force sensor. Fig. 5 shows the reference forces and the slide forces measured after static calibration. In the in process calibration, the signals are measured during up and down milling, where only the cutting depth is changing. The reference forces are provided by a dynamometer. The filtered reference forces and the filtered z-slide forces after calibration are mapped in Fig. 6. It shows that the z-slide forces can be approximated well with standard linear regression for both calibration methods. The calculated deviations of the z-slide forces to the reference grow up to maximal 10 % in the range of 500 N. The force resolution of the z-slide is about 10N. The calculated slide forces based on the offline calibration is also depicted in Fig. 6. A

comparison of these forces with the reference forces shows the deviations which can occur if using the unsuitable force calibration method.
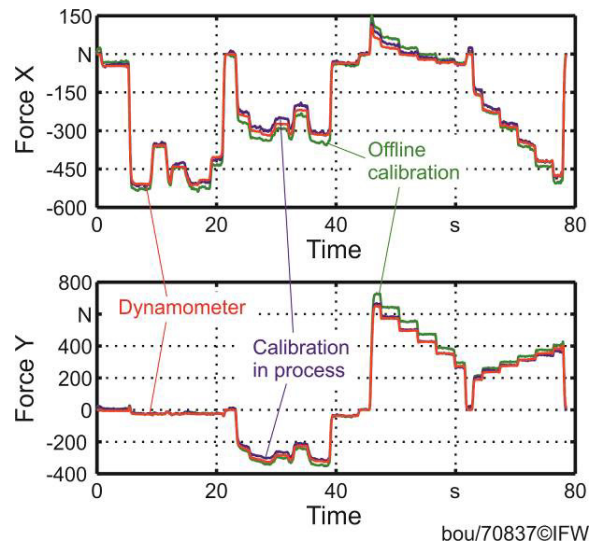
Fig. 6. Calibration of the z-slide forces using process signals.

5. Detection of the tool deflection

The stiffness of a body presents the ratio of the applied force on that body to the caused deformation. To measure the stiffness, both deformation and force have to be measurable. In case of the z-slide, the stiffness measurement can be executed in the machine tool by a soft collision of the tool with the work piece. Here, the z-slide moves slowly into the workpiece, until contact is detected. From that position the slide continues the movement for a set distance. With the known set distance and the measured force, the stiffness of the z-slide can be calculated. Fig. 7 shows the changes on the z-slide force and the tool path during a collision along the x direction with a set collision distance of 150 µm, whereby a tool with 12 mm diameter is used. Since the change in the colliding force is detected by the z-slide and the driven distance is assigned by the machine tool control, the stiffness of the z-slide with all relevant components for the process like the linear guide, the spindle, the tool holder and even the tool, is determined. Such a measurement of the z-slide stiffness could be a very helpful way for example to parameterize simulations for machine tools.
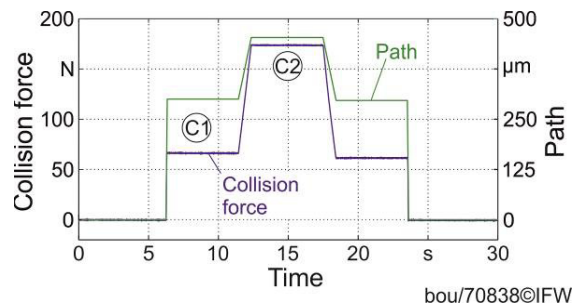
Fig. 7. Measured force and tool path by a soft collision with the work piece.

During a soft collision the displacement of the z-slide is measured in addition externally with laser triangulation sensors at the locations L1 to L7 (Fig. 8), where L1 is located on a linear guiding carriage of the z-slide. This

measurement enables the determination of the relative deformation of the z-slide going from the reference location L1. L8 is measured on the workpiece side to detect its deformation and slipping during the collision. It shows that the tool (L5 to L7) presents the part on the z-slide with the highest deformation (Fig. 8). In the collision, most of the set collision distance is converted into tool deflection.

In milling, the tool is statically deflected due to the process forces in the same way as by the collision. To estimate the static tool deflection in the process, the clamped tool in the tool holder can be modelled as a cantilever beam. The tool deflection w at the position x along the tool axis due to the concentrated force F can be determined for $0 < x < a$ by:

$$w = \frac{Fx^2(3a - x)}{6EI} \qquad (1)$$

otherwise by:

$$w = \frac{Fa^2(3x - a)}{6EI} \qquad (2)$$

where a is the position of the concentrated force, E is the modulus of elasticity and I is the area moment of inertia of the tool [6]. The bending stiffness (EI) can be estimated by the soft collision, while a is set equal to the tool length L. The distance a in milling can be formed as function of the depth of cut a_p, assuming the force transmission point at the half of a_p:

$$a = L - \frac{a_p}{2} \qquad (3)$$

As F is measurable by the z-slide, L and a_p are set parameters, the tool deflection during milling can be estimated based on (1) and (2).
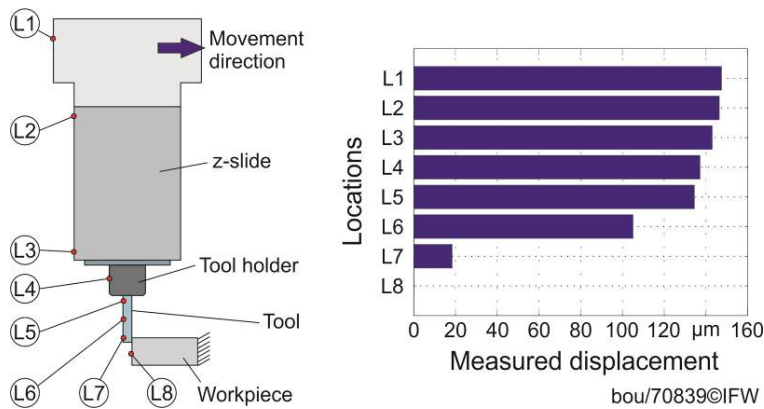

Fig. 8. Measurement of the z-slide deformation.

In order to verify the measurement of the tool deflection, the deflection has to be provoked during milling. This is achieved by milling of pre-machined surfaces showing alternating ridges of about 0.25 mm depth and 10 mm width. The milling process is executed with a tool of 12 mm diameter. The depth of cut is set to 40 mm. In order to provide reference surface curves, the machined surfaces of the workpieces are measured additionally after milling using a perthometer at 3 different positions A, B and C along the depth of cut: A at the top, B at the middle and C at the bottom of the surface. Fig. 9 shows the surface curves measured with the perthometer and the z-slide. Because of the

alternating ridges on the surface, the process forces on the tool are changing so that the tool deflection is changing as well. From the top and the buttom curves of the perthometer the deflection of the tool along the depth of cut can be approximated to about 55 μm. The curves measured by the z-slide at the position A, B and C correlate with the reference curves on these positions very well. The deviation of the slide curves to the reference is smaller than 10 μm and can be explained by the used simplified deflection model which supposes a perfect clamped beam with ordinary geometry.
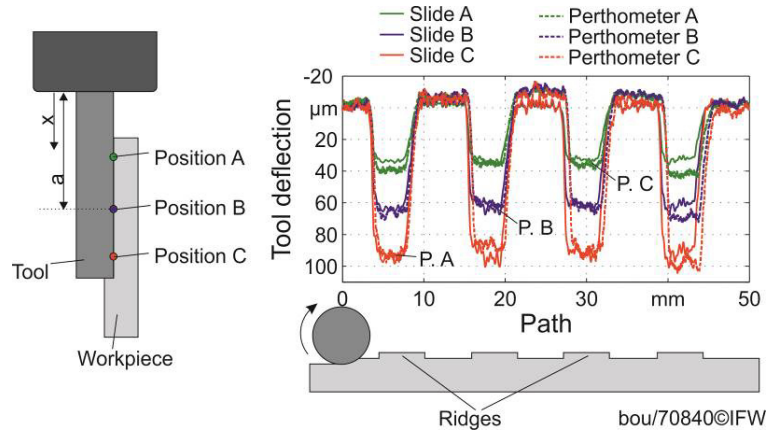
Fig. 9. Measurement of the tool deflection.

6. Conclusion

The presented paper shows latest results from the development of a sensory axis-slide for "feeling machine tools". This research is conducted in the collaborative research center 653. The main function of the sensory slide is to detect the process forces during milling by measuring the structure strain. First, a prototypical slide with two kinds of small strain gauges is presented. A method to improve the sensitivity with small notches in the structure is explained and the sensing behavior is analyzed experimentally. The results show that the sensitivity is increased significantly and the main stiffness of the slide is not affected by the sensor integration. Furthermore, due to the dependence of the force calibration on the load type applied at the TCP, two strategies for force calibration are discussed and tested experimentally. A force resolution of about 10 N at 500 Hz sample frequency thus is feasible. Finally, the bending stiffness of the tool is determined by executing a soft collision of the tool with the work piece. In order to estimate the tool deflection, the clamped tool on the tool holder is modelled as a cantilever beam. The real-time detection of the tool deflection during milling is demonstrated and the measured deflection signals are compared to reference measurements with a perthometer. It shows that the deflection values provided from the slide correspond to the reference. Future research will focus the development of "feeling" work pieces which will be able to detect thermal effects of the machining process and to provide information about their own deformation.

Acknowledgements

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