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INCREASING PRODUCTIVITY OF CUTTING PROCESSES BY REAL-TIME COMPENSATION OF TOOL DEFLECTION DUE TO PROCESS FORCES

The Internet of Production (IoP) describes a vision in which a broad range of different production data is available in real-time. Based on this data, for example, new control types can be implemented, which improve individual manufacturing processes directly at the machine. A possible application scenario is a tool deflection compensation. Although the problem of tool deflection is well known in the industrial field, a process-parallel compensation is not common in industrial applications. State-of-the-art solutions require time and cost consuming tests to determine necessary cutting parameters. An NC-integrated compensation that adapts the tool path in real-time will make these tests obsolete and furthermore enables higher chip removal rates. In this paper, a control-internal real-time compensation of tool deflection is described, which is based on a process-parallel measurement of process forces. The compensation software is designed as an extension to the NC kernel and thereby integrated into the position control loop of an in-series NC. The compensation movements are generated by manipulating the reference values of the feed axes. The approach is investigated by experiments with linear axis movements. During these tests, a significantly reduction of geometrical machining errors is possible.

1. INTRODUCTION

The success of manufacturing companies depends on their ability to manufacture their products efficiently and profitably. Therefore, efficient and precise machine tools are essential in metalworking industry. Working accuracy of machine tools is influenced by a large number of error sources. In addition to the geometric and kinematic deviations, which occur during the manufacturing process, the elastic load and deformation behaviour of the machine is significant. Machine deformations result among other things from thermal loads, weight forces, mass inertia forces and process forces. A large part of machining error is caused by tool displacement due to process forces. Common strategies to reduce tool-deflection such as decreasing finishing allowance, multiple overruns or using suitable

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cutting parameters extend processing times and require tests or at least corresponding empirical knowledge for determining a proper strategy and the parameters.

1.1. RESEARCHES ABOUT TOOL DEFLECTION COMPENSATIONS / REDUCTIONS

In order to avoid additional manufacturing times or tests [1, 2] append a tool-deflection compensation functionality in the CAM framework by post processing the generated NC-code. Hereby, the additional software generates a shifted NC-code. The shift is calculated based on simulated process forces. This approach is called “offline” compensation, because the compensation movements are calculated prior to machining. Advantages of these approaches are that neither modifications nor additional components are required at the machine. A major disadvantage is that the simulation must exactly represent the later process. Since the process forces are determined decisively by the feed rate or tool wear, the dynamics of feed axes and tool wear must also be considered in simulation. This leads to a more complex and machine specific model. Both effects are neglected in [1, 2]. Furthermore, machines are generally not able to follow NC-code exactly due to their limited dynamics. The target path calculated by the software to compensate deflections is therefore usually not the real path in the manufacturing process. Additionally unforeseeable events such as an override change by the operator or workpiece inhomogenities cannot be considered in simulation.

“Online” approaches aim to compensate or at least reduce tool deflection parallel to the machining process and are therefore able to react on unforeseeable events. Hence the amount of deflection is adjustable within limits by changing the feed rate, [3] developed a control system which reduces tool deflection by adapting the feed rate based on a real-time measurement of process forces. For measuring purposes, [3] built a force sensing spindle slide. Besides reducing the tool deflection, this approach inevitably increases manufacturing time. Furthermore frequently changing feed rate during cutting decreases surface quality.

Other “online” approaches, that directly compensate tool deflection, often use additional and complex mechatronic components in order to generate the compensation movements. [4] developed an adaptronic milling spindle which uses piezo actors to move and tilt the entire spindle. A 3D-dynamometer, which the workpiece is mounted to, measures the process forces. [5] built a tool holder that enables tilting the milling cutter. The amount of tilt is adjustable while machining and because of the lever arm (tool length), compensation movements can be created at the tool tip. A force measuring component is also integrated in the holder system. All these systems lead to significant improvements regarding the deviation from the target path and the geometric error caused by tool tilting and bending. However, these approaches require expensive and complex additional components, which increase the overall machine costs. Furthermore, they are additional potential error sources, because of their complex mechatronic structure, and decrease flexibility of the machine. To avoid additional active components [6] uses the feed axes of the machine to generate compensation movements. Thus, only a measuring device is required. The compensation functionality is integrated in a custom-made numerical control and manipulates the reference value inputs of the position controller of each feed axis. [7] integrated a real time simulation model in the numerical control, to additionally avoid force measuring devices. For realizing fast computation times, a highly pre-calculated model is used. Its pre-calculated parameters are determined in CAM-software and defined in each sentence of the NC-code, which contains movements. In contrast to [1, 2], the simulation is performed parallel to the process and uses control-internal data so that control related process changes, such as the use of the feed rate override, are considered. [8] implemented a complex simulation model into the numerical control of a lathe. Based on machine-internal data, the model calculates process forces via Kienzle equations and afterwards the resulting static tool-deflection. Therefore, neither measuring nor active components are required. The approach achieves significant improvements in simple turning operations.

1.2. MOTIVATION

Many offline and online studies that try to minimize tool displacements have already been conducted. Solutions which use the feed axes to generate the compensation movements are of particular interest, because they do not require additional components except a measuring device. Although the process forces are of great importance, they are generally not recorded sufficiently in in-series machines during machining. This is where the vision of industry 4.0 comes in, for which all process data should be available in real time. In the meantime there are some promising approaches that could fix this lack of data shortcoming in the near future [3, 9, 10]. Thereby, additional measuring equipment is no longer required and control internal displacement compensations would become mere software components. This major advantage is offset by the delay behaviour of the feed axes. In addition, filters are generally used for the further processing of the measured forces, which cause additional delays. In the case of rapid process changes the cumulative latency can lead to the fact that the displacement is not sufficiently compensated for in a purely reactive manner and that incorrect compensations may even occur under certain circumstances. The compensation movement has to be initiated in advance to be able to equalize the issues caused by latency.

Such an approach is discussed in this paper and compared with a purely reactive compensation. Thereby the NC core of an in-series machine control is extended with a compensation functionality, which runs in the position control cycle time. In addition to the process forces measured in real-time by a force measuring platform, the compensation functionality uses data about the future feed rate for calculations. The determined displacement is superimposed to the reference value of the corresponding feed axis. The compensation is evaluated based on a feed rate step during a linear milling operation and the process where the cutter is exiting the workpiece. In the validation, purely reactive compensation and those that take future feed rate into account are compared with each other. Overall, the results show the general applicability of the approach and its application limits.

The potentials offered by industry 4.0 in terms of displacement compensations are not limited to just providing process forces. However, industry 4.0 is still at the beginning of its development and therefore the identification of opportunities is yet very visionary and will thus be discussed later in the outlook.

2. DESIGN OF THE COMPENSATION

Before the two compensations – one proactive and one pure reactive – and their integration into the control system are explained in more detail, restrictions that form the framework of the concept should first be defined: For reasons of simplification only the static part of the displacement that is orthogonal to the current feed and tool axis direction is compensated. This simplification is only permissible for straight milling operations in which tangential displacement components do not cause manufacturing errors. Only the tool tip displacement is compensated; the geometric error caused by tool tilting and bending is ignored. To determine the static displacement, the static process force is transformed using the serially connected static stiffness of the machine and the tool. The compliance of the workpiece is neglected. Since the integrated process force measuring systems mentioned above are still in development, a piezoelectric force measuring platform is used in this analysis.

2.1. INTEGRATION INTO THE NUMERICAL CONTROL

The schematic design of the discussed deflection compensations is illustrated in Fig. 1. As shown in the figure, the deflection compensations run in the numerical control kernel, more precisely in its position control cycle. Since the deflection compensations are designed as an NC kernel extension, a wide range of control internal data can be read and used for calculations at runtime.

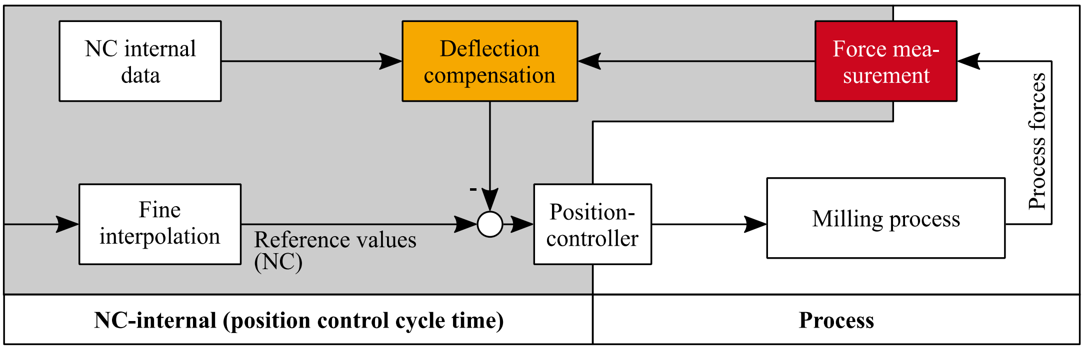

Fig. 1. Schematic structure of the described deflection compensations

The current reference velocity and current reference acceleration of each axis are the control-internal inputs of each deflection compensation. The second share of inputs are the current process forces, which must be provided in real time to the deflection compensation. Therefore, the workpiece is mounted on a piezoelectric force measuring platform which is connected via Profinet IRT (Isochronous Real Time) to the numerical control (NC: in-series Sinumerik 840D sl of Siemens AG). Based on the provided data, the deflection compensation calculates a position offset for each feed axis, which is later subtracted from the corresponding reference value and thus compensation movements are generated.

2.2. STIFFNESS MODEL OF MACHINE AND TOOL

In many approaches the compliance of the machine is neglected [1, 7], but this is only permitted in special cases where the compliance of the tool is significantly higher [11]. To make the present compensation more general, the static machine stiffness is taken into account. Actually, the machine stiffness depends on the position, but is assumed to be constant here. This simplification is implemented because the additional static compliance of the tool reduces the static stiffness span of the entire system (machine and tool). The effect can be illustrated formally: The minimum static stiffness of the overall system $k_{\min}$ may be described by the constant static stiffness of the tool k_t and the minimum static stiffness of the machine $k_{M,\min}$. The latter is formed by the static mean machine stiffness k_M and the span of the static machine stiffness Δk_M:

$$k_{M,\min} = k_M - \frac{\Delta k_M}{2} \tag{1}$$

$$k_{\min} = \frac{k_t \cdot k_{M,\min}}{k_t + k_{M,\min}} = \frac{k_t \left(k_M - \frac{1}{2}\Delta k_M\right)}{k_t + k_M - \frac{1}{2}\Delta k_M} \tag{2}$$

The same considerations apply to the maximum static overall system stiffness $k_{\max}$:

$$k_{M,\max} = k_M + \frac{\Delta k_M}{2} \tag{3}$$

$$k_{\max} = \frac{k_t \cdot k_{M,max}}{k_t + k_{M,max}} = \frac{k_t \left(k_M + \frac{1}{2}\Delta k_M\right)}{k_t + k_M + \frac{1}{2}\Delta k_M} \tag{4}$$

The difference between maximum ($k_{\max}$) and minimum static stiffness of the entire system ($k_{\min}$) yields the span of the entire static stiffness. A comparison with the span of the static machine stiffness Δk_M illustrates that the span of the overall static system stiffness is always smaller than that of the machine and converges asymptotically towards the machine span as the tool stiffness increases.

$$\Delta k_M \geq k_{\max} - k_{\min} = \frac{k_t^2 \cdot \Delta k_M}{(k_t + k_M)^2 - \frac{1}{4}\Delta k_M^2} \tag{5}$$

For implementing the compensation the static stiffness of the machine was measured beforehand in X- and Y-direction at only one position. The static stiffness of the tool including the holder was obtained by means of an FEM simulation, which is verified by measurements. Due to the symmetric tool shape, only one stiffness value is calculated but used in X- and Y-direction. The overall static stiffness of the entire system is determined by the mathematical series connection of the individual stiffnesses.

2.3. INTERNAL DESIGN OF THE COMPENSATION

In the following, the internal structure of the displacement compensations is described. This paper examines two different controllers, a proactive one and a purely reactive one. Figure 2 shows the structure of both controllers. The components with solid lines are the same for both controllers. The dotted components are only included in the proactive controller for imitating the proactive character and will be described later. Each controller uses a filter to determine the static displacement component. However, the filter is plotted dashed dotted, since the controllers use different filters.

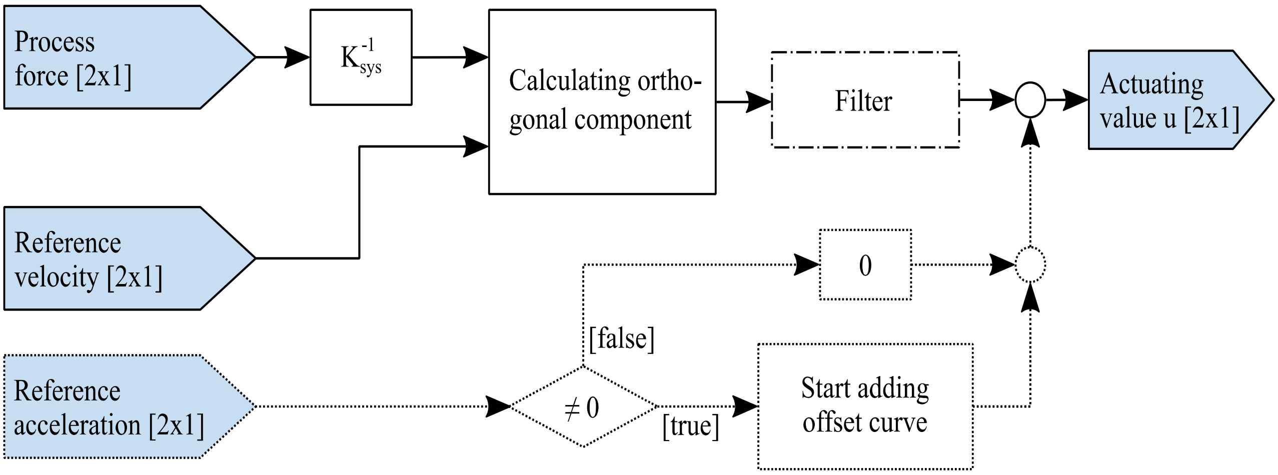

Fig. 2. Schematic internal design of the deflection compensations

First, the current displacement is approximated from the vector of the measured process force via the matrix of the static system stiffness (K_{sys}). The vector of the current reference feed is then used to determine the displacement component orthogonal to the feed direction. Finally, that component is filtered to obtain the orthogonal static displacement. As mentioned above, the controllers differ regarding the applied filter.

To ensure that the purely reactive controller has a low reaction time, a chain of notch filters is used for filtering. Each notch filter is adapted to a specific cutter engagement frequency. The bandwidth b_w of the filters is defined relative to the center frequency $f_{0,i}$ of the corresponding filter. The center frequency is determined by the spindle speed n [1/min] and the number of cutting edges N.

$$f_{0,i} = \frac{n}{60} \cdot i \qquad i = 1, \ldots, N \tag{6}$$

$$b_w = \frac{f_{0,i}}{4} \tag{7}$$

In order to smoothen the process forces further and at the same time achieve a low delay behaviour, a first-order low-pass filter with a cut-off frequency of 120 Hz is superimposed on the notch filter chain.

The proactive controller uses a second-order low-pass filter with a cut-off frequency of 6 Hz and a damping ratio of D = 1. This is significantly slower than the notch filter chain but makes the controller more robust. The disadvantages with regard to the latency are to be compensated by the proactive behaviour. In general, the data that is currently available parallel to the process is not sufficient for designing a controller with general foresight. Nevertheless, in order to achieve a proactive behaviour, a specific offset curve was determined in a reference test, which the desired behaviour is simulated with. During the real test, this offset curve is only superimposed to the actuating value for a short period at the feed rate step according to Fig. 2.

Figure 3 illustrates the response of each controller to a previously recorded force measurement (blue). To clarify the effect of the offset curve, a reactive controller with a 6 Hz second-order low-pass filter, which is the basis of the proactive controller, is also shown. The curves are distinctly step-shaped, since the position control cycle time of the numerical control and thus the sample rate is at 500 Hz.

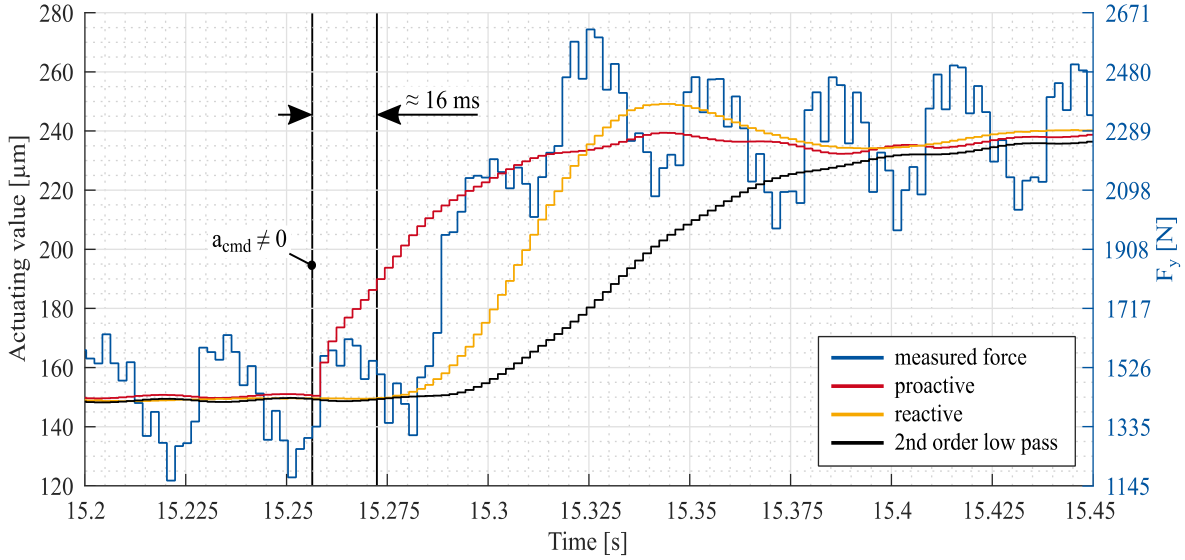

Fig. 3: Controller response to a previously recorded force measurement (sample rate: 500 Hz)

At the time when the reference acceleration in the recorded measurement is unequal to zero ($a_{\mathrm{cmd}} \neq 0$), the offset curve is superimposed and thus the actuating value precedes the input signal. The distance between the second-order low-pass (black) and the proactive controller (red) is caused by the offset curve. Furthermore, Fig. 3 illustrates the significantly faster response of the notch filter chain (yellow) compared to the second-order low-pass filter with 6 Hz and $D = 1$. The 16 ms given in Fig. 3 is the delay time of the feed axis of the machine, which was used in this paper.

3. VERIFICATION

The experiment is carried out using a cuboid workpiece made of C45 steel and a carbide end mill (diameter: 16 mm, number of teeth: 5) which is clamped in a shrink chuck. Fig. 4 illustrates the milling operations performed. The test cuts are complete full-grooves (a_e = 16 mm, a_p = 8 mm, spindle speed S = 1990 1/min). The feed rate is abruptly increased from 500 mm/min to 1000 mm/min in the NC-code after half of the machining process, which causes a step in deflection that is visible at the groove walls. After machining the walls are measured by a contour measuring device.

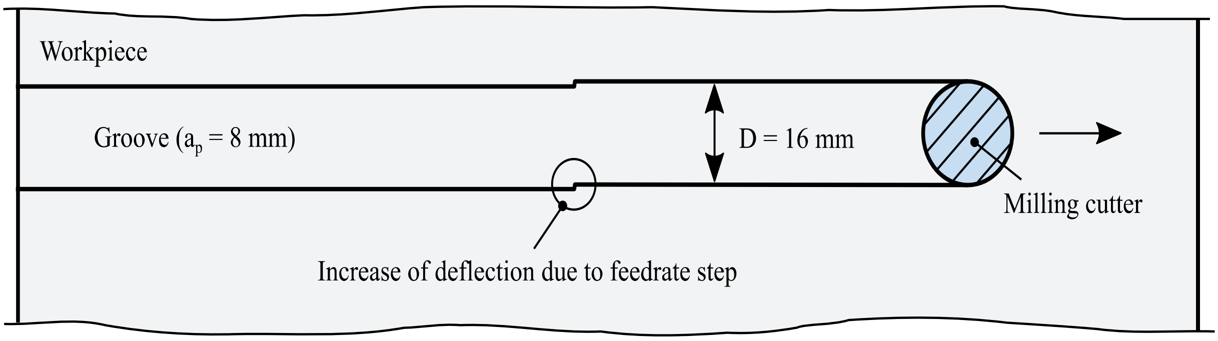

Fig. 4. Test setup with complete groove and feed rate step

3.1. RESULTS

The displacement compensations were investigated using the test described above. The curves shown in here illustrate the contour measurements at the groove walls of the various experiments. In addition to the measured curves of both controllers, Fig. 5 also contains a curve of a test without compensation to show the possibilities and suitability of the general concept (both “proactive” and “reactive”).

Under constant process conditions the general concept of this approach works well. By using one of the compensations, the geometric error can be partially reduced by 95% during the test. On the one hand this confirms that the ignoring of the machine rigidity in a general displacement compensation is not permissible and on the other hand it shows the suitability of the selected filters. However, the measuring records also confirm the assumption that changing process conditions are a big challenge for displacement compensations.

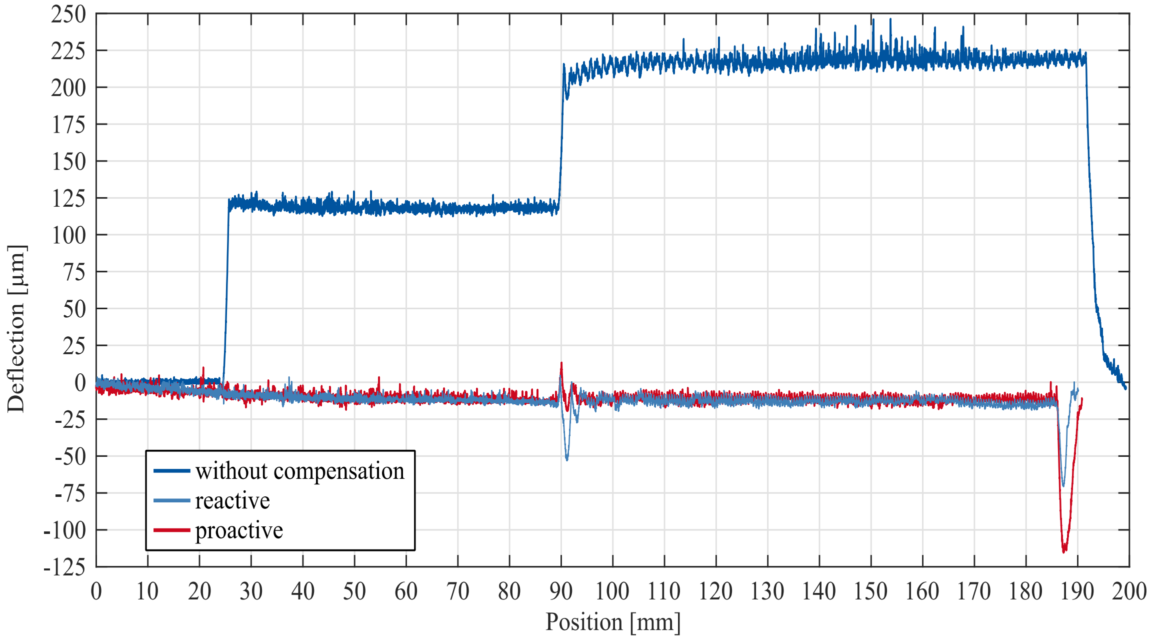

Fig. 5. Comparison of compensations by contour measurements at the lower groove wall. Due to different blank sizes, the curves vary in length and are aligned at the feed rate step

At the feed step (at approx. 90 mm), the controllers have different characteristics (proactive and reactive). During the process where the cutter is exiting the workpiece (at approx. 185 mm) both are purely reactive, since no offset curve was determined for this section. Both of the mentioned areas are of particular relevance in this paper and will therefore be discussed in more detail below.

3.2. FEED RATE STEP

Since the feed axes carry out their nominal values only in a delayed manner and calculating the static displacement component causes further delays, a purely reactive displacement compensation is not able to avoid the displacement peak. The pure reactive controller reduces the peak to 74 µm, but the applied notch filter chain leads to a decaying oscillation behaviour at the feed rate step (see Fig. 6), which is also found in the actuating values of the controller and therefore cuts visible notches in the walls. The more robust second-order low-pass filter does not have this tendency to vibrate. If this filter were designed purely reactive, a larger peak would be expected due to the higher latency of the filter. However, since the peak here is significantly lower (43 µm), the advantage of proactive compensations is shown. The compensation is robust and at the same time capable of significantly reducing the deflection step. The offset curve of the proactive controller was obtained using a reference test (see Chapter 2.3). However, using the controller changes the real process so that the offset curve will never match the process perfectly. It can therefore be assumed that the best results were not yet achieved and that further reductions of the peak are therefore possible.

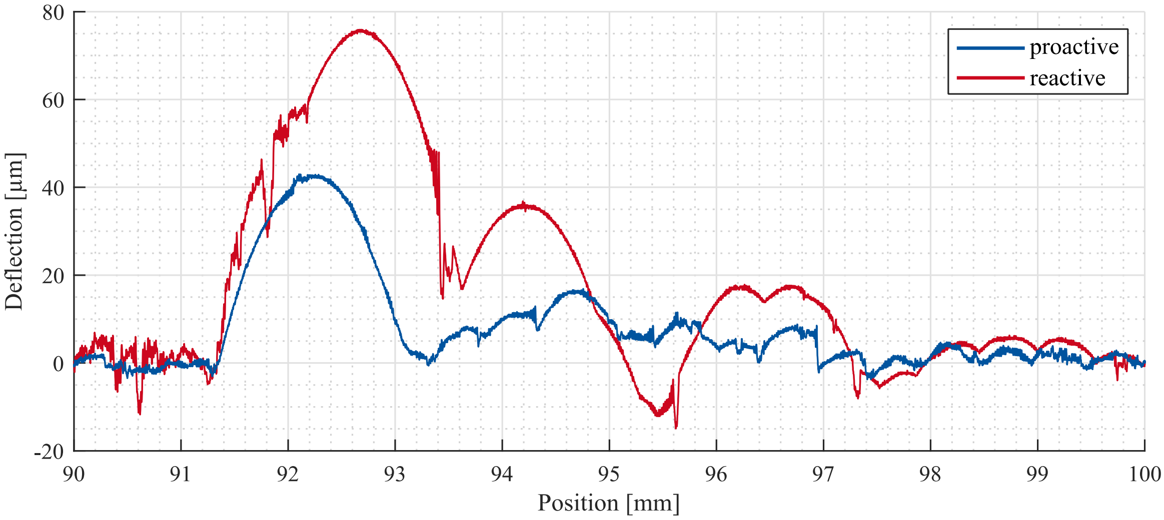

Fig. 6. Deflection peaks at the upper groove wall during feed rate step

3.3. EXITING PROCESS

Both compensations are only reactive during the process where the cutter is exiting the workpiece, because no offset curve was determined here. In the uncompensated mode, the displacement is reduced to 0 µm, but always remains positive (see Fig. 5). Using one of the compensations causes a negative displacement (undersize), since the actuating value is not reduced fast enough. The slower the applied filter, the greater the effect. Therefore, a fast reaction time of the controller is decisive. Especially in the applied test, the exiting process is a big challenge, since the milling cutter exits first at exactly that point where previously the largest orthogonal process force component was generated. As a consequence, the orthogonal process force drops particularly quickly here. If the engagement width a_e is smaller, the effect should be lower. Nevertheless, negative displacement is a general problem of displacement compensations. Due to the delayed behaviour of the feed axis and the filters this can generally only be prevented by proactive compensation.

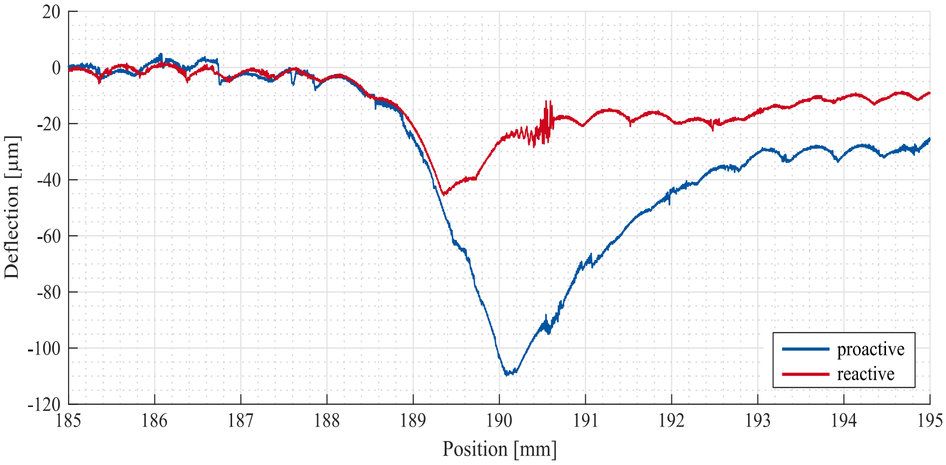

Fig. 7. Deflection notches at the lower groove wall during exiting process

4. CONCLUSION

A major problem in machining today is the displacement of tools by process forces. Typically, the control loop of a machine tool closes with the position control loop; everything that happens behind it is unknown to the numerical control [12]. Many approaches have already been investigated to compensate for this displacement. Technologies that do not require any additional components and do not restrict operating during the process are desirable. Particularly promising are those approaches that run parallel to the process in the control and use the feed axes to generate the compensation movements. Especially under constant process conditions, a significant reduction in deflection can thus be achieved. So far, the tests have only been carried out using a milling operation along one machine axis. First tests with different feed directions and contours in the XY plane indicated improvements as well. Nevertheless, this must be further verified.

Due to the use of the feed axes, however, there is always a delay element in the control loop of the compensation. In case of fast process changes, this and the additional latency of the filter leads to an insufficiently fast reaction and thus to faulty compensation. This problem can be solved by proactive compensation. In order to estimate the potentials of such a displacement compensation, a comparison of a proactive and a purely reactive compensation was carried out in this paper. A linear milling process was used as a benchmark, in which the compensations were investigated more closely on the basis of a feed rate step and the process where the cutter is exiting the workpiece. It turned out that due to the proactive character the compensation can be designed more robustly and that at the same time predictable process changes are significantly better compensated.

The proactive behaviour could only be imitated in the context of this investigation. With regard to the feed rate step, a solution that combines a process force measurement and a process-parallel predictive force simulation could already be implemented today. The simulation could use the reference feed rate instead of the actual one for calculation and thus achieve a brief forecast. Similar to the principle of the Kalman filter, the controller could rely more on the measurement when the feed rate is constant and more on the simulation when the feed rate changes.

4.1. POTENTIALS OFFERED BY INDUSTRY 4.0

For the realization of a general proactive control, which considers abrupt changes of the cutter engagement, additional data is required that is generally not yet available. The vision of industry 4.0 can, however, create the necessary foundations here. Especially the concept of the digital twin seems promising. Digital twin means that the machining process is represented digitally and virtually parallel to the process [13]. Thus, there is always a model available that matches the current state of the workpiece and machine. Both the current workpiece geometry and the engagement would then be known. From this data a brief look into the future – the delay behaviour of the feed axes of the machine used in this investigation is in the low two-digit millisecond range – could then be dared and a proactive control realized. Due to the short prediction period, the forecasting model could be verified during operation using the actual values. If a drift is detected, the forecasting model could be adjusted. However, the capabilities offered by foresight are not limited to displacement compensations, but form the basis for a variety of developments.

The computation of a process-parallel digital twin and therewith a possible forecast is intensive and requires resources, which are generally not provided by present numerical controls. Industry 4.0 offers a solution here as well. Due to the networking of production, the necessary calculations could be outsourced to specialized computers and just the calculated actuating values could be transmitted back to the numerical control. Of course, there are limitations in terms of communication speed, but the increasing performance of bus systems suggests that this problem can also be solved.

Digital twin not only offers possibilities for forecasting, but also for verifying and improving the displacement compensation itself. Even today, there are approaches that optimize the NC code after manufacturing based on the digital twin. With a similar approach the displacement compensation respectively the applied models could be optimized, ideally in a self-learning process.

Even though the mentioned ideas are still very theoretical and visionary, it is possible to imagine the potentials that industry 4.0 offers in terms of process-parallel optimization functionalities such as a displacement compensation.

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