Edited by
Berend Denkena
Tobias Mörke

Cyber-Physical and Gentelligent Systems in Manufacturing and Life Cycle

Genetics and Intelligence – Keys to Industry 4.0
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3.2.5 Online monitoring and control of tool deflection in milling

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3.2.5.1 Introduction

Systems for online process monitoring and control in milling are widely used. They allow early detection of process failures such as chatter \[1\], tool wear, tool collision, tool breakage \[2,3\], and clamping failures \[4\]. Furthermore, they support the manufacturer in case of detected failure by stopping immediately the machine axis or try even to stabilize the process \[5\]. Resulting failure costs can be ultimately reduced. However, previously developed systems are generally restricted to optimizations regarding process load \[6\] or process stability \[5\]. Approaches for process quality monitoring and control have been subject to only little research.

The tool deflection represents one of the most important quality-degrading effects in milling. It occurs generally in any cutting process due to the compliance of the used tool and process forces and causes a deviation between the real and the reference path of the tool. The results are shape and dimension failures on the workpiece side. Required manufacturing tolerances can no longer be maintained. Furthermore, especially in the processing of complex free-form geometries and in finishing processes, the tool deflection has a decisive influence on the productivity.

For the online monitoring of the tool deflection during manufacturing, a process force signal and the knowledge of the stiffness of the used tool are indispensable. The developed “feeling” machine tool in CRC 653 \[7\] is already able to measure the process forces on its tool center point (TCP). Based on a machine-integrated force sensing system, a measuring cycle is developed and implemented into the machine control, allowing the identification of the tool stiffness, within the machine tool \[8,9\]. Since the tool deflection can be monitored by known process forces and tool stiffness, it can be even controlled \[10\].

This chapter shows the development of a monitoring and control system for tool deflection as an assistance system for milling operations. First, the machine-integrated identification of the tool stiffness is described. Based on the provided force signals from the “feeling” machine and the identified tool stiffness, a model for detection of the tool deflection is presented. Finally, a feed-based tool deflection control is realized by adjusting the axis feed using a data communication between the monitoring system and the machine control.
3.2.5.2 Detection of tool deflection

The stiffness of the tool represents 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. The stiffness measurement can be carried out in the “feeling” machine tool through a soft collision of the tool with the workpiece. Here, the spindle slide of the machine is driven slowly into the workpiece until a contact force is detected. From that position, the slide continues the movement for a predefined distance of some micrometers. With this known distance and the measured force deviation, the static stiffness of the spindle slide can be calculated. Fig. 3.2.5.1 shows the deviation of the force and the tool path during a collision along the feed direction with a predefined collision distance of 150 μm using a tool with a diameter of 12 and 70 mm length. The change in the collision force is detected by the developed spindle slide of the “feeling” machine tool and the collision distance is assigned by the machine tool control. The stiffness of the spindle slide can be determined with all relevant components for the process such as the linear guide, the spindle, the tool holder, and even the tool.

During a soft collision, the displacement of the spindle slide was also measured externally with laser triangulation sensors at the locations L1 to L7 (Fig. 3.2.5.2), where L1 was located on a linear guiding carriage of the spindle slide. This measurement enables the determination of the relative deformation of the spindle 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 spindle slide with the highest deformation (Fig. 3.2.5.2). 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 during the collision. To estimate the static tool deflection in the process, the clamped tool in the tool holder can be modeled as a cantilever beam. Due to

![Fig. 3.2.5.1 Measured force and tool path by a soft collision with the workpiece.](image-url)
the concentrated force $F$, the tool deflection $w$ at position $x$ along the tool axis can be determined by:

$$w = Fx^2(3a - x)/6EI \quad (3.2.5.1)$$

for $0 < x < a$, otherwise by:

$$w = Fa^2(3x - a)/6EI \quad (3.2.5.2)$$

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. The bending stiffness ($EI$) is estimated from the soft collision, while $a$ is set equal to the tool length $L$. The distance $a$ in milling can be formed as a function of the depth of cut $a_p$, assuming the force transmission point at the half of $a_p$:

$$a = L - a_p/2 \quad (3.2.5.3)$$

As $F$ is measurable by the spindle slide and $L$ and $a_p$ are set parameters, the tool deflection during milling can be estimated based on Eqs. (3.2.5.1), (3.2.5.2).

In order to verify the measurement of the tool deflection, the deflection has to be provoked during milling. This is achieved by milling of premachined workpieces which show alternating ridges of about 0.25 mm depth and 10 mm width. The milling process is carried out with a tool of 12 mm diameter and 70 mm length. 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 three different positions A, B, and C along the depth of cut: A at the top, B in the middle, and C at the bottom of the surface. Fig. 3.2.5.3 shows the surface
curves measured with the perthometer and the spindle slide. Because of the alternating ridges on the surface, the process forces on the tool are changing, which means that the tool deflection is changing as well. From the top and the bottom 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 spindle slide at positions A, B, and C correlate very well with the reference curves on these positions. 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.

3.2.5.3 Feed-based control of the tool deflection

In order to reduce the tool deflection and to achieve the desired manufacturing tolerances, the tool deflection has to be controlled while machining. The main objective of the control loop (Fig. 3.2.5.4) is to maintain the actual tool deflection $d_{Act}$ while milling constantly at a desired reference deflection $d_{Ref}$ despite of disturbances in process
by adjusting the axis feed of the machine. Such disturbances may be, for example, unexpected fluctuations in allowances in casting parts that cause changes in the cutting parameters like the cutting width \(a_c\) or the cutting depth \(d_p\) within a straight path. The actual deflection is measured by the sensory spindle slide and is compared to a given reference, which can be calculated from the required shape and dimension tolerances of the workpiece. The occurring difference \(e\), called also the residual error, is applied to the control system, which provides the required feed override \(OVR\) for the machine control. For safety reasons, a signal limitation is integrated at the input of the machine control, so that the feed override can be varied only between 0% and 120%.

For the implementation of the control loop, an industrial PC with real-time controller and programming environment TwinCAT3 from Beckhoff is used. The used “feeling” machine tool is equipped with a machine control of type Siemens SINUMERIK 840d [10]. The override signal of the control system and further command signals are transferred between the industrial PC and the machine control via PROFINET communication. The signal transfer on the Siemens control is performed by programming synchronous actions, which are implemented within the NC program. The signals can be read out in the interpolation cycle rate of the controller achieving a sampling rate of maximum 250 Hz.

The required control for tool deflection should be fast enough to react quickly to changes in the measured deflection signals and accurate to eliminate completely the detected residual error. Furthermore, the control should show a quiet behavior by providing the override signal for the machine control. Disturbances in the override can cause damage to the machined surface and the control application has no more benefits. PID controllers are probably the most used controller structures in industrial applications. However, for the deflection control, the PID controller may be unsuitable because of the unrest of its derivative component in combination with noisy signals. Instead, a PI controller is more suitable for this control task. It combines the advantage of the P controller, namely, the rapid response to error, with the exact settling of an I-controller. The PI controller is fast and accurate. Its manipulation algorithm is in Eq. (3.2.5.4), where \(k\) is the number of sample, \(K_p\) the gain of the

![Control loop for tool deflection.](image)
P-controller, the $K$, the gain of the I-controller, $T_a$ the sample time, and $OVR_{mid}$ the initial override value:

$$OVR_k = K_p \cdot e_k + K_i \cdot T_a \cdot \sum_{0}^{k} e_k + OVR_{mid}$$  \hspace{1cm} (3.2.5.4)

The initial override value $OVR_{mid}$ is set to 70% to allow the controller settling in both directions. To get an effective starting point for the controller tuning, the second method of Ziegler-Nichols is used \cite{11}. This method is practicable for systems, whose transmission behavior is unknown or not easily identifiable, and which can be driven to their stability limits without causing damages. Under this method, only the P-controller is activated in the control loop. Fig. 3.2.5.5 shows the deflection signal at the stability limits by applying the Ziegler-Nichols method in several milling processes with different values of proportional gain $K_p$. The test is performed for a reference deflection $d_{Ref}$ equal to 80 $\mu$m and constant cutting parameters with exception of the axis feed. The initial override $OVR_{mid}$ of 70% corresponds in this test to an initial feed $F_{mid}$ of 2000 mm/min. The deflection control is started within the air cutting, 15 mm before reaching the workpiece. The gain $K_p$ is increased step by step up to 1.75. At some critical value $K_{cri} = 1.25$, sustained oscillation in the signal of the measured deflection with corresponding period $T_{cri} = 0.145$ s occurs for the first time. Based on

![Deflection signal at stability limit while controller while tuning.](image)

<table>
<thead>
<tr>
<th>Process parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N = 5000$ rpm</td>
</tr>
<tr>
<td>$F_{mid} = 2000$ mm/min</td>
</tr>
<tr>
<td>$D = 10$ mm, $Z = 6$</td>
</tr>
<tr>
<td>$a_p = 17$ mm</td>
</tr>
<tr>
<td>$a_x = 0.5$ mm</td>
</tr>
<tr>
<td>$C_{tool} = 3.78$ N$\mu$m</td>
</tr>
</tbody>
</table>

Fig. 3.2.5.5 Deflection signal at stability limit while controller while tuning.
the notified critical values, the controller gains $K_p$ and $K_i$ can be set with respect to the tuning method as following:

$$K_p = 0.45 \cdot K_{cri}$$  \hspace{1cm} (3.2.5.5)

$$K_i = K_p / (0.85 \cdot T_{cri})$$  \hspace{1cm} (3.2.5.6)

Fig. 3.2.5.6 shows the deflection signals by using the PI controller with its determined parameters for varied references between 70 and 100 μm. The process parameters and the control starting conditions are the same as in the tuning test. Generally, it shows that the measured deflection signal follows well the set references. The settling behavior of the controller with respect to determined controller parameter appears accurate and quiet. However, high overshoots appear in the measured signal. They show up also significantly over the first 20 mm of the workpiece surfaces.

In Fig. 3.2.5.7, the signals of the controller test by a reference of 80 μm are plotted. As previously mentioned, the control is already switched on within the air cutting before the tool reached the workpiece. So no deflection is occurring and a positive residual error is established. Consequently, the control begins increasing the feed override in order to increase the tool deflection and to reduce the existing error. However, the tool deflection stays unchanged and the feed override exceeds immediately and significantly the upper limitation of the machine control. As the tool attends the workpiece and the material cutting begins, it comes to a change of sign of the residual error and the I-controller begins reducing its output. That takes time until the output reaches again the upper limit of the override and until the error is settled to zero. In this way, an overshooting is produced at each beginning of material cutting. Such overshooting is a typical problem for control loops with I-controllers in combination with limited system input and is known as the windup effect. Technically, many antiwindup solutions and algorithms exist and allow maintaining the controller output at the upper limit. They may reduce the settling time of the residual error. However, they are not able to decrease the overshooting amplitude, because the tool is still hardly entering the workpiece with the maximum axis feed.

A promising solution to damp the overshoots is to shift the starting time of the deflection control. As shown in Fig. 3.2.5.8, starting the control as a material cutting
Fig. 3.2.5.7 Control signals while deflection control by 80 μm.

Fig. 3.2.5.8 Different starting strategies for the deflection control.
is detected allows a significant decrease of the overshooting amplitude and even the settling time in comparison with previous starting while air cutting. That is because the tool deflection is occurring during material cutting and is responding to the override changes provided by the controller. In this way, the controller output stays mostly within the limitation area of the machine control and the tool is no more reaching the workpiece with the maximum axis feed. Furthermore, starting the control first as the tool deflection reaches the reference shows smoother entering of the tool into the workpiece with only small overshoots.

To assess the presented control approach regarding cutting accuracy and cutting time, milling tests are performed with varying cutting widths and constant cutting depth. The test steps are shown in Fig. 3.2.5.9A. In the first step the workpiece is prepared by machining a ramped shape. In the second step the milling of a straight path is performed. During this step, the ramp simulates a variation of the cutting width between 0.5 and 1 mm and causes a changing in tool deflection. In the final third step, the marginal positions of the workpiece are measured by a touch probe allowing the determination of the resulting shape offset. The process is repeated 10 times, with and without deflection control. In Fig. 3.2.5.9B the results of the process tests are depicted. It shows that processes with deflection control produce considerably smaller shape offsets compared to uncontrolled processes. Consequently, the milling is performed

![Fig. 3.2.5.9 Setup for tool deflection evaluation tests (A). Results of milling tests (B).](image-url)
more precisely by using the deflection control despite of changing cutting width. However, controlled processes take significantly more time due to permanently changing axis feed by the control.

A further control restriction factor for the deflection control is the override limitation on the machine control side. The override limitation bounded the area of the axis feed and therefore limits the permissible cutting width in process (Fig. 3.2.5.10). If the actual cutting width lies outside of the permissive area of the cutting width, the deflection control cannot be done entirely without error. The permissible area of the cutting width grows with increasing reference deflection.

**3.2.5.4 Conclusion**

As the products are becoming more and more individual, intelligent manufacturing systems are required to reduce additional costs in comparison to conventional series productions. This chapter presents an approach for a monitoring and control system for the tool deflection, one of the most frequent process failures in milling. The monitoring system is realized by using a “feeling” machine tool, which is able, on the one hand, to sense online the occurring process forces by integrated strain gauges in its sensory spindle slide, and on the other hand, to measure autonomously the tool stiffness. The control system allows to maintain the measured tool deflection constantly at a set reference value despite of disturbances in process like unexpected changing in the cutting parameters. The control loop is based on a PI controller with the benefits of fast and accurate settling. The controller parameters are determined experimentally with respect to the method of Ziegler-Nichols. It shows that the control starting condition has a big influence on the settling behavior of the controller and on the overshooting amplitudes. Starting the control within the material cutting allows smoother entering of the tool into the workpiece and damps therefore overshoots. Further process tests show that the deflection control increases significantly the milling accuracy but also the cutting time.

![Fig. 3.2.5.10 Boundary cutting width for deflection control.](image)
## References


## 3.2.6 Tempering control of forging processes by integration of cavities

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### 3.2.6.1 Introduction

Powder metallurgy and its parts have gained significant importance in the metal processing industry in recent years. It is known for its high potential to produce near net-shape products. In view of a higher percentage of material utilization and comparably lower energy costs, powder metallurgy processes fulfill the requirements of modern manufacturing. The primary objective of this work is to develop a forging die which can “feel,” “learn,” and “control” autonomous reactions to process...