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Paper:

Improvement of the Static and Dynamic Behavior of a Milling Robot

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Because of the high flexibility and low investment costs, industrial robots are increasingly being employed for machining processes. However, milling robots can only be used for applications requiring low accuracy and minor cutting forces. The main reason for this is the low static and dynamic stiffness of the robot structure, which lead to huge deflections of the tool and heavy chatter oscillations, especially when steel is being machined. To extend the areas in which milling robots are applied, a model-based controller to compensate for path deviation has been developed at the Institute of Machine Tools and Industrial Management of TU Munich (iwb). In addition, process-based strategies to reduce chatter have been analyzed. This paper focuses on the dynamic behavior of robots to increase the stability of the cutting process, but it also gives an overview of the design of the controller for static deviation compensation.

Keywords: milling, robot, chatter, compensation

1. Initial Situation

To get an overview of the behavior of a robot during machining operations, milling tests on aluminum and steel were performed with a prime robot (KR 240 R2500, KUKA). **Fig. 1** presents the results of the cutting tests. During the machining of a circle and a rectangle on workpieces of aluminum (slotting, Aluminum EN AW-2007, depth of cut $a_p = 5$ mm, tool diameter $d = 12$ mm, number of teeth $z = 3$, feed per tooth $f_z = 0.09$ mm, spindle speed $n = 9300$ rpm), force-induced deviations that are strongly direction dependent and that have a maximum amplitude of up to 1 mm can be observed. These deviations are the main reason why manufacturers are reluctant to use robots even for machining operations with moderate cutting forces. Another issue is the high propensity for chatter during milling operations on steel. During the experiments, several chatter oscillations occurred even at low depth of cut (slotting, steel C45E, $a_p = 2.1$ mm, $d = 12$ mm, $z = 3$, $f_z = 0.055$ mm, $n = 3200$ rpm), as shown in **Fig. 1** (bottom).

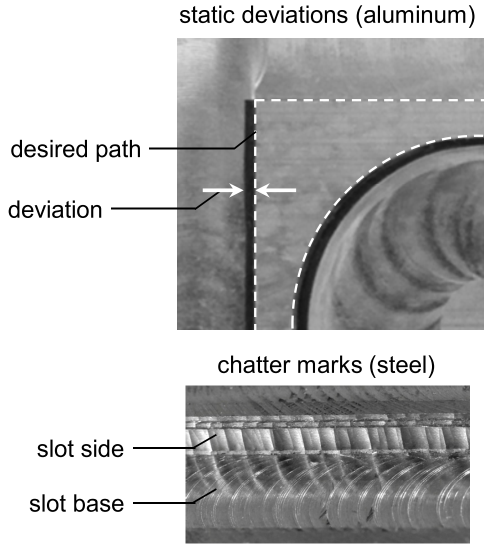


Fig. 1. Static deviations and chatter on workpieces of aluminum and steel.

2. Model-Based Controller to Compensate for the Static Deviations of the Tool

To compensate force-induced static deviations of the Tool Center Point (TCP) during the milling process, a model-based position controller can be used [1]. Because of the high costs that are associated with measurement systems such as laser trackers to detect the position of the TCP with the necessary accuracy, the path deviations are determined indirectly using the cutting forces, as shown in **Fig. 2**.

The controller is not part of the robot control, but there is User Datagram Protocol-based (UDP) communication with a cycle-time of 4 ms between these systems. This is so that the axis angles and the cutting forces, which are measured with a dynamometer, can be used as input signals for the controller. With this information, the force-induced deviations of the TCP are calculated and contrary offset signals are generated to correct the command values of the robot's internal position control.

To implement for the deflection compensation, a real-time model of the robot, a model that includes all relevant compliances of the structure, has been developed. The

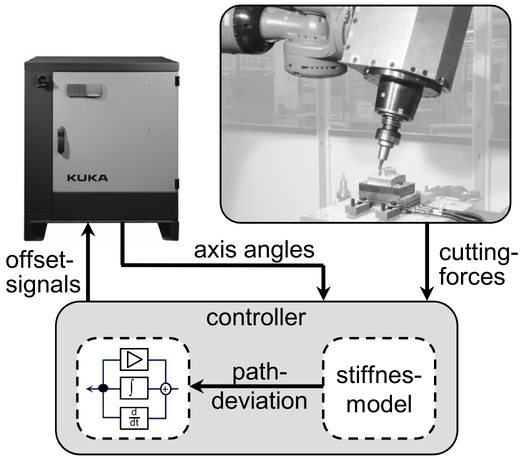
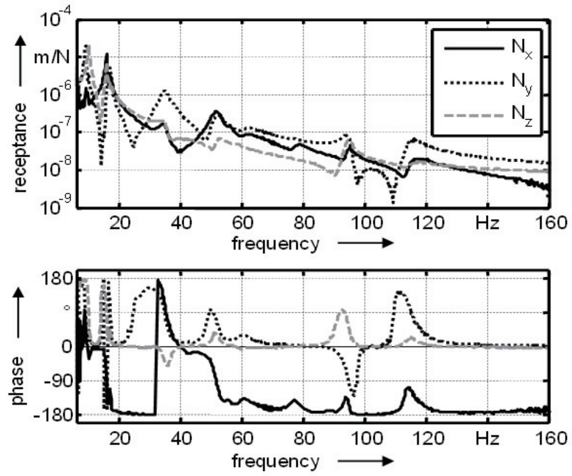


Fig. 2. Structure of the robot system including the controller to compensate for path deviations.



mode	Frequency in Hz	Damping in %
1	8.9	1.5
2	10.0	1.2
3	15.9	1.0
4	17.0	1.7
5	35.0	3.7
6	51.7	3.1
7	94.4	1.4
8	116.2	2.7

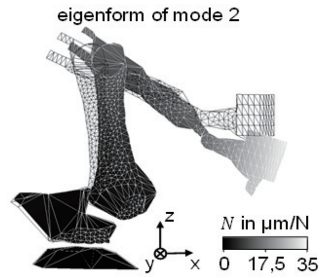


Fig. 3. FRF at the spindle flange in the x, y, and z directions (top), identified eigenmodes (bottom left) and eigenform of mode 2 (bottom right).

simulation model is based on conventional forward kinematics, where the single coordinate frames are deflected to consider the flexibility of the gears, bearings, and structural components of the robot. Besides a very low calculation time, the model is valid for the main working area of the robot. A major challenge regarding the model has been the determination of the relevant compliance parameters. These have been determined by a single measurement setup with a 3D-scanning Laser Doppler Vibrometer (LDV) (PSV-400-3D, Polytec) while the robot has been loaded with a defined force at its TCP. A detailed description of the simulation model and the parameter estimation is given in [1]. With the use of the model-based controller, static path deviations could be reduced by 85%.

3. Analysis of the Dynamics of the Robot

To identify possible methods of reducing chatter, several experiments were carried out to analyze the dynamics and the process behavior of the robot.

3.1. Modal Analysis

The structural dynamics were identified by exciting the robot at the tool holder of the spindle with an inertia actuator (SA10, CSA Engineering) in a space diagonal direction. Unclear why the word “space” has been added here. With the use of an adapter, it was possible to detect the amplitude of excitation with a force measurement cell (1051V3, Dytran). The actuator was loaded by a chirp signal (sinusoidal sequence with linear increase in frequency) within a frequency range of 6 to 500 Hz (measurement time: 100 s). The response of the robot was measured by a 3-D accelerometer (8762A10, Kistler) that was mounted at the flange of the spindle with a magnet. **Fig. 3** (top) shows the frequency response function (FRF) for the $x-$, $y-$, and $z-$directions. These have been calculated using the H1-norm [2] and a complex mean value of the three single measurements.

Additionally, the figure shows the natural frequencies and the corresponding damping factors that were calculated using the peak amplitude method [3]. Within a frequency range of 6 – 160 Hz eight eigenmodes with partially very high dynamic compliance, N can be identified. To analyze the corresponding mode shapes, the robot was loaded by the actuator with a sinusoidal force for every specific natural frequency while the system response at 550 points was measured using the LDV. With this procedure, a steady state vibration was achieved that allowed an accurate and effective detection of the mode shapes. This is because every measurement point needs to be recorded for only a few oscillation periods. The mode shape of the eigenfrequency at 10 Hz (**Fig. 3**, bottom right) shows a dominant movement of the TCP in the $z-$direction. In contrast, mode 1 at 8.9 Hz represents an oscillation of the TCP in the orthogonal (y) direction in such a way that the first two modes build a critical pair regarding the chatter effect of mode coupling. A comparable pair is built by modes 3 and 4. The modal analysis of the robot shows a huge number of eigenmodes within a relevant frequency range regarding milling operations. That explains the high propensity for chatter that was observed in section 1.

3.2. Process Stability

The process stability of a machine can be systematically analyzed by an experimentally identified stability lobe diagram. For that reason, slots were milled in staged

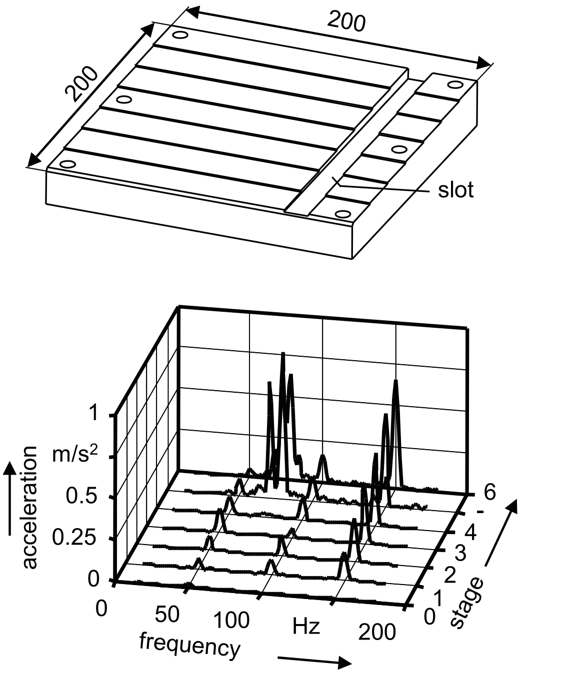


Fig. 4. Staged workpiece (top) and operational vibration spectra of the acceleration at the spindle flange in the $y-$direction (normal to the feed direction, bottom).

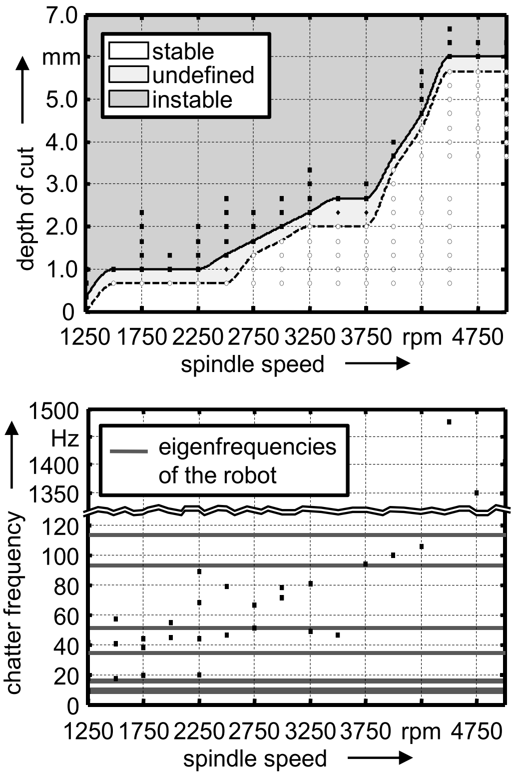


Fig. 5. Stability lobe diagram (top) and corresponding chatter frequencies (bottom).

workpieces, as shown in **Fig. 4** (top), to increase the depth of cut in discrete steps. For all slots, the feed per tooth was constant; only the spindle speed was changed. The processing sound and the operational deflection of the robot (high frequency oscillations of the spindle system) were measured with a microphone and at the flange of the spindle (low frequency oscillations of the robot structure) with a 3-D accelerometer. The measurement signals were assigned to the individual steps and transformed into the frequency domain to identify chatter vibrations and their frequencies. **Fig. 4** shows the vibration spectra of the acceleration at the spindle flange during cutting for every stage of the slot that was machined with $n = 3000$ rpm (steel C45E, $a_p = [0.66, 1, 1.33, 1.66, 2, 2.33, 2.66]$ mm, $d = 16$ mm, $z = 3$, $f_z = 0.055$ mm). Before the tool reached stage 5 ($a_p = 2$ mm), only oscillations with the frequency of the spindle speed (50 Hz) and its harmonics at 100 and 150 Hz (tooth passing frequency) are present. At the next step, an abrupt increase of the vibration amplitude at 71 Hz and 79 Hz can be observed, a clear indication of chatter. For this spindle speed, the critical depth of cut is $a_{cr} = 2$ mm.

Within the tests on steel, n was varied in a range of 1250 rpm to 5000 rpm with a step-size of 250 rpm. The resulting stability lobe diagram is shown in **Fig. 5** (top). The single experiments are labeled as stable (○), unstable (■) and slightly unstable (♦). The corresponding chatter frequencies are illustrated at the bottom of the figure.

The propensity of the robot for chatter at low spindle speeds is very high. In the speed range from 2500 to 3750 rpm, an increase of a_{cr} to 2 mm is obtained. Higher spindle speeds result in a significant improvement of a_{cr} to almost 6 mm, where the stability is limited by an audible high frequency vibration of the cutter. During an unstable process, the chatter frequencies cannot be clearly assigned to the eigenmodes. This is caused by the closed flux of forces during machining which leads to large frequency shifts, especially in a structure with high elasticity, such as a robot.

4. Reduction of the Chatter-Affinity

To improve the process stability and to reduce chatter, different process-based methods exist. In the following sections, these methods are presented and evaluated for their suitability in robot-based machining operations.

4.1. Utilization of the Spindle Speed Dependency of the Process

A typical stability lobe diagram of a machine tool shows a recurring alternation of local stability minima and maxima with increasing spindle speed, followed by the absolute stable speed, above which no regenerative chatter is possible. The stability lobe diagram of the robot being investigated (**Fig. 5**) does not show local stability maxima because of the high number of natural frequencies, which are all close together. Therefore, the superposition of the lobes shows no significant minima and maxima. Hence, the method of choosing processing parameters in regions with high local stability cannot be used. Nevertheless, it is possible to use the speed dependency of the process stability in order to identify suitable processing parameters, because every eigenmode of the structure will reach its stable area successively with increasing speed. A consideration of the highest observed chatter frequency allows for the determination of the final stability minimum. The relation between the chatter frequency f_c and the speed n can be described by the following equation [4]:

$$n = \frac{f_c \cdot 60}{z \cdot \left(i + \frac{\varepsilon}{2\pi}\right)}, \quad i = 0, 1, 2, \ldots \quad \ldots\ldots \quad (1)$$

where i is the integer number of waves that are cut on the workpiece by two sequential teeth of the cutter and ε denotes the phase relationship between the oscillation of the current and previous tooth. The last stability minimum persists when no full wave is cut on the workpiece between two teeth ($i = 0$) at a phase-shift of $\varepsilon = \frac{3\pi}{2}$. For the system under investigation, this speed can be calculated to $n = 2827$ rpm ($f_c = 106$ Hz, $z = 3$). For higher spindle speeds, the stability of the process increases exponentially. The machining experiments and the analytical prediction of the stability lobes of a 1 DOF system at the highest chatter frequency have shown that the speed at which regenerative chatter of the robot structure can be avoided can be estimated by the following:

$$n > 1,7 \cdot \frac{f_c \cdot 60}{z \cdot \frac{3}{4}} \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

However, n cannot be chosen in that region for every tool because the resulting cutting speed leads to high thermal loads and excessive tool wear. In this case, the same effect can be achieved by using tools with higher numbers of cutting edges. In order to validate the effectiveness of this approach, milling experiments with staged workpieces (**Fig. 4**, top) using cutters with 4 and 5 teeth ($n = 2250$ rpm, $d = 16$ mm, feed $f_v = 371$ mm/min) were carried out and compared to the results in **Fig. 5** ($z = 3$). Achieving the same material removal rate, the critical depth of cut increased from 0.66 mm (3 teeth) to 2.33 mm (4 teeth) and to 3 mm (5 teeth), respectively. These values have been identified by analyzing the operational vibration spectra of the acceleration at the spindle flange, as described in section 3.2. As an exemple, the results for the tool with 5 teeth are shown in **Fig. 6**. Up to a depth of cut of 3 mm, only oscillations with integer multiples of the spindle speed (37.5 Hz) occur. At a depth of cut of 3.33 mm and above, the abrupt increase in the vibration amplitude at 105 Hz clearly indicates process instability.

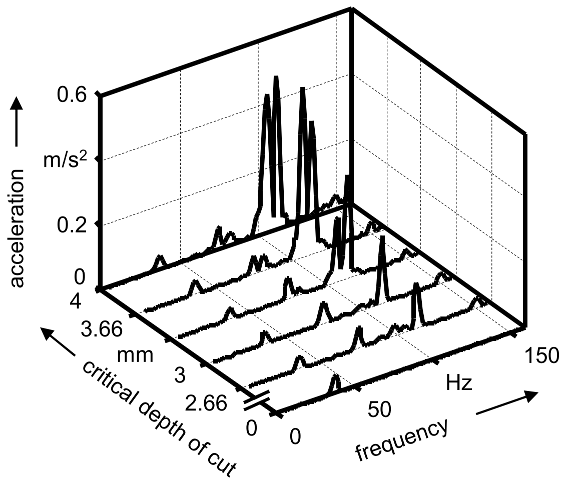


Fig. 6. Operational vibration spectra of the acceleration at the spindle flange in the y−direction (normal to the feed direction) for a tool with 5 teeth.

4.2. Use of Unevenly Spaced Cutters

In addition to raising the spindle speed or the number of teeth, utilizing tools with variable pitch angles can reduce the regenerative chatter effect. The mechanism of regenerative chatter is then disrupted because the variable pitch angles lead to a periodically varying phase shift of the teeth entry so that no chatter oscillations arise. The best stabilization effect is achieved if the regenerative force of each tooth cancels out that of the others. For that reason, the pitch angles need to be adjusted to the spindle speed and the chatter frequency, as described in [5] or [6], for different kinds of irregular pitch variations. Because of the low chatter frequencies of the robot at low spindle speeds, a tool geometry optimization results in very irregular pitch angles ($[17.7°, 120°, 222.3°]$). A tool like this is difficult to produce. It also leads to widely varying cutting widths, which make the dynamic force load on the robot very high. In a machining experiment with a standard variable pitch angle tool $[80°, 100°, 80°, 100°]$, the critical depth of cut was increased by 0.66 mm compared to the tool with $z = 4$ and a constant pitch angle ($n = 2250$ rpm, $d = 16$ mm, $f_v = 371$ mm/min). Thus, the use of tools with non-uniform geometry is only partially suitable for robotic milling operations.

4.3. Periodic Spindle Speed Variation

Periodic Spindle Speed Variation (SSV) may also be used to disrupt the mechanism of regenerative chatter. During the machining process, the spindle speed changes in either a sinusoidal or a triangular way with the ratio of the amplitude (RVA) and the ratio of the variation frequency (RVF) as parameters. The SSV parameters must be adapted to the particular machine and process [7]. For the milling robot and the previously described process (slotting, $z = 3$, $n = 2250$ rpm, $d = 16$ mm, $f_v =$ 371 mm/min), RVF = 8% and RVA = 18% were identified as suitable, simulating a milling process, as described in [8]. With these parameters, an experiment on the staged workpiece (**Fig. 4**) was performed. **Fig. 7** shows the measured spindle speed over time (top) and the resulting vibration spectra during cutting (bottom). In addition to the fact that there is no improvement in the critical depth of cut, the plot shows an oscillation with huge amplitude at 3 Hz. This vibration is also present before the tool enters

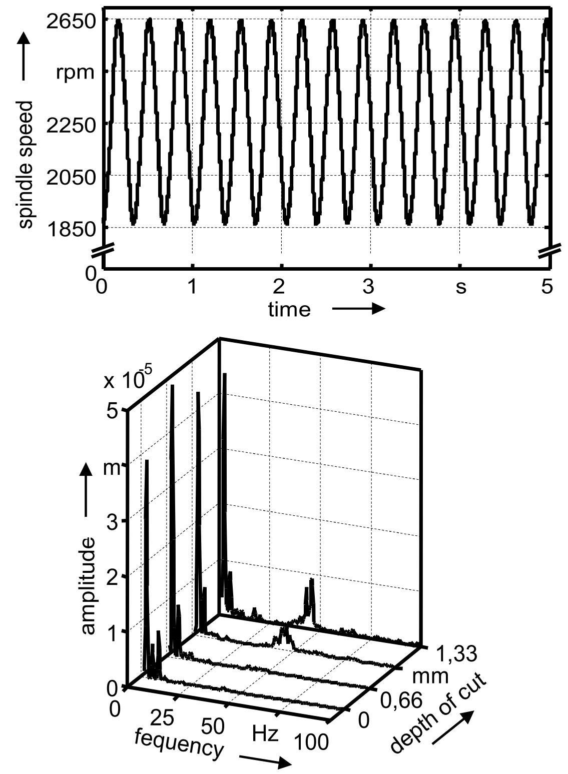


Fig. 7. Measured spindle speed with active SSV (top) and operational vibration specra of the displacement at the spindle flange in $y-$direction, bottom).

the workpiece ($a_p = 0$ mm) and is excited by the spindle speed variation (3 Hz).

The high amplitude is caused by the low dynamic stiffness of the robot, even if there is no eigenmode within that frequency range. For that reason, SSV can only be applied on spindles with small rotating inertia by using an amplitude and frequency ratio that keeps the excitation of the robot limited to a minimum.

5. Summary

During milling operations with industrial robots, the interaction between the process and the elastic mechanical structure leads to huge static deviations and a high propensity for chatter in the system. In this paper, different process-based approaches from the field of machine tools were investigated. The analysis showed that the utilization of the dependency of the spindle speed on stability could be used in robotic machining operations. The empirical formula presented can be used to estimate the spindle speed, depending on the chatter frequency and the number of teeth, to be used to avoid regenerative chatter. This allows steel to be cut at decent depths of cut. Other methods, such as the use of a non-uniform tool geometry or the periodic variation of the spindle speed, can only be restrictively applied on milling robots. In combination with the model-based controller to compensate for static deviations of the tool, milling robots can be an economical alternative to conventional machine tools in various areas, such as the machining of large structures in the aerospace industry.

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