MACHINE TOOL

Process stabilization with an adaptronic spindle system

Berend Denkena · Olaf Gümmer

Abstract For economical reasons it is necessary to reduce the machining time and to increase the process automation. This leads to the need for fast machine tools with high process stability in order to enhance the material removal rate. However, the machine often does not limit the process stability but the tool because of its compliance. This paper presents a new possibility of expanding the stable process range of long and slender end mills with an adaptronic spindle system. The system is able to position the spindle dynamically in the range of microns with three piezo actuators. In order to disturb the regenerative effect, which leads to an instable process, the chip thickness is modulated by a dynamic spindle actuation. This is realized by a superposition of vibrations of the tool in feed direction. In milling tests the degree of stabilization is verified for different superpositions. Hence, the stable process range could be improved for spindle speeds up to 5,000 rpm.

Keywords Machine · Milling · Spindle · Stability · Adaptive control

1 Introduction

The increasing economic pressure caused by the globalization forces machine tool manufacturers to develop new concepts. In addition, the conflict between precision and productivity requires new technology solutions for machine tools [1]. Beside the demand of high material removal rate and increased precision, the availability of a machine tool is of particular economical importance. In order to reduce costs, it is necessary to increase the degree of automation. Thus, monitoring of the machine conditions and process stability is essential for a reject-free mechanical production [2].

Machine tools often operate at their physical constraints in order to achieve maximum productivity. However, the machine often does not limit the material removal rate and machining speed, but the tool. During milling, especially long and slender end mills quickly tend to cause instable process conditions and inaccuracies in the form of tool deflections because of its high compliance.

In order to fulfill these requirements, the integration of mechatronic components into the machine tool structure becomes more and more a main research field. The integrated sensors can be utilized for monitoring.

In this paper an adaptronic spindle system is presented, which can actively actuate a milling spindle. With a new approach the appearance of instable process conditions, especially for milling processes with long and slender end mills, can be delayed up to higher metal removal rates by a superposition of vibrations in milling direction. Thus, the stability range can be enhanced and the productivity of the machine can be improved. The superposition of vibrations is achieved by an active tilting of the spindle with a specific frequency and amplitude.

1.1 State of the art

1.1.1 Stabilization of milling processes

Milling belongs to the class of multi-point machining operations where the cut is intermittent and periodic with tooth passing intervals [3].

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In the past years, a lot of research has been done on modeling and prediction of the process stability, particularly due to its importance in high speed cutting. In Altintas et al. [3] listed up the fundamental theories of modeling of cutting processes. The simulation and prediction of cutting processes, their stability and the appearance of chatter are objects of verification in [4] and [5].

A milling process is defined as instable if chatter vibrations rise up. The appearance of chatter leads to tool and machine wear. In order to avoid that, the material removal rate has to be reduced.

The most common and detrimental phenomenon, which leads to chatter vibrations, is the effect of regenerative vibrations. Surface marks left at the previous path produce the self-excitation of a natural frequency of the machine tool system. This leads to a modulation of the chip thickness and therefore causes a self-excitation of the process [7, 8] as shown in Fig. 1.

The appearance of chatter depends on the static and dynamic stiffness of the machine tool and the milling parameters [9]. The process is affected by the tool geometry, the influence of inner and outer modulation, the run-out and non-linearities such as tool jumping out of cut and past multiple-regeneration waviness caused by all teeth [3].

The stability of a cutting process can be determined in stability lobe diagrams. Based on experimentally measured compliance frequency response functions, the stability can be calculated in dependence of the milling parameters, tool geometry and other boundary conditions as shown in [9].
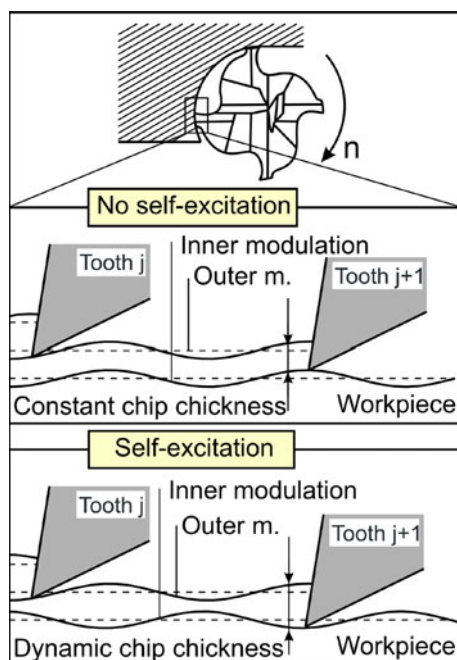
These diagrams show the chatter stability of a machining system as a function of the cutting depth and spindle speed.

As well as the prediction of chatter, the passive prevention of chatter is researched. There are several approaches to prevent the regenerative effect and therefore extend the stable process range. The amplification of regenerated vibrations in milling processes can be avoided by an unequal feed per tooth. In [10] this approach is realized with a continuous spindle speed variation. Other attempts to improve the stability of milling are spindle speed regulation [11], a variable helix tool [12] and variable pitch cutters [13]. All of these approaches increase the stable stock removal volume for certain milling parameters.

1.1.2 Mechatronic systems for machine tools

For the active optimization of machine properties, mechatronic components are developed for machine tools. In [14] a milling spindle with an additional magnetic bearing between the tool and the conventional bearing is presented. The additional magnetic bearing can apply damping forces to enhance the stability of the process. A similar approach is described in [15]. Here, spindle-integrated piezo actuators are positioned at the bearing close to the Tool Center Point (TCP) to actively damp and stabilize the milling process. In [16] an approach of a milling spindle with a motor-integrated embedded electromagnetic actuator to actively reduce chatter vibrations and to increase the productivity is analyzed.

An adaptive spindle support with piezo actuators externally attached to the milling spindle is presented in [17]. Here, the parallel kinematic design of the piezo actuators allows a precise quasistatic and dynamic positioning in five degrees of freedom for the active position correction of the tool.

References [18–20] present mechatronic workpiece holder systems, which actively compensate chatter vibrations by using piezoelectric actuators. Further mechatronic systems to improve the properties of machine tools are presented in [1] and [21].

1.2 Adaptronic spindle system

The Institute of Production Engineering and Machine Tools (IFW) at the Leibniz Universität Hannover developed an adaptronic spindle system (AdSpin) for milling machines. The objective is a dynamical hybrid positioning of a conventional spindle in the range of microns in order to compensate static and dynamic tool deflection and vibrations of long and slender end mills.

For the active spindle positioning, three piezo actuators are arranged around a conventional milling spindle in a

Fig. 1 Formation of chatter by regenerative vibrations [6]
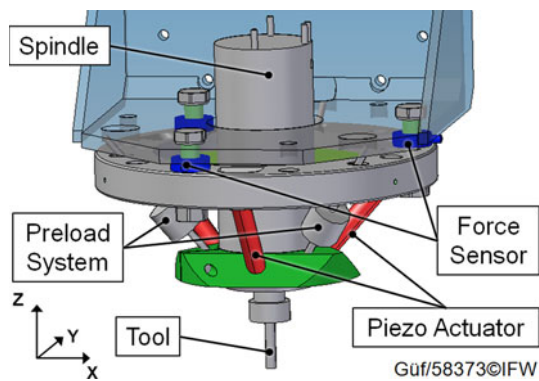
Fig. 2 Adaptronic spindle system (AdSpin)

parallel kinematics configuration (Fig. 2). This allows a dynamic positioning of the spindle (up to 2,000 Hz) in three degrees of freedom within a range of ±100 μm depending on the tool length. The parallel kinematics configuration enables a high static and dynamic stiffness that is mandatory for stable cutting processes [3]. Figure 2 shows a CAD model of the adaptronic spindle system.

The piezo actuators are preloaded by three preload systems consisting of disk springs to protect them from tension. The spindle is mounted at the bottom of the three actuators along a tensioning ring. A steel membrane, which is fixed on the frame in the middle of the spindle, holds the torque around the z-axis but allows small rotations around the x- and y-axis. Thus, the tool tip can be moved inside a prismatic space. For machining tests AdSpin is mounted in a vertical three-axis milling machine (Fig. 4).

In addition to the strain gauges on each piezoelectric actuator, which allow a closed-loop position control, the sensor system is extended by three quartz load washers to measure the forces during a milling process. Further information on the assembly, the sensor system and the results of the research on the AdSpin concerning tool deflection compensation and vibration damping are published in [22] and [23].

The tool deflection of an end mill with an overhang length of 65 mm could be compensated significantly by more than 80 % [24, 25]. Furthermore, vibrations of up to 1,500 Hz could be damped [25, 26] by generating specific counter-vibrations.

The existing sensors of the AdSpin can be used for process monitoring as well. By measuring the process forces, tool wear can be monitored and instable process conditions can be detected [27, 28].

2 Active process stabilization

Previous mechatronic systems attempted to increase the stability by active damping. In contrast, the described

methods in Sect. 1 increase the stability by an interruption of the regenerative effect by varying the feed per tooth. Hereby, the feed per tooth can be varied only within certain limits.

A new approach for an active variation of the feed per tooth is given by the adaptronic spindle system. The idea is to superpose vibrations in feed direction to vary the feed per tooth and thereby to avoid chatter. The feed per tooth can be varied in a large range because of a tool movement of about ±100 μm. This possibility to stabilize a milling process has been analyzed.

To verify the active process stabilization, preliminary slot milling tests were carried out with an end mill with the following specifications: diameter 12 mm, three blades, material HSS PM/F, $\lambda = 30°$, $\gamma = 15°$, overhang length 65 mm. The feed rate was 500 mm/min at a rotational speed of 5,000 rpm. These milling parameters correspond to a nominal feed per tooth of 33 μm. Thereby, the material AlMg4,5Mn was machined. Experimental investigations showed that at a depth of cut of about 0.2 mm the process becomes instable. To verify the active process stabilization, a cutting depth of 0.75 mm is selected. At this depth of cut the process is clearly in an instable range without stabilization.

2.1 Control of superposed vibrations

For the active process stabilization, a control has been developed and integrated into the control system of AdSpin [24]. The control calculates the frequency of the superposed vibrations in dependence of the spindle speed n and the number of teeth z. The amplitude of the superposed vibrations can be varied up to 100 μm. Simulations of the blade movement point out that the continuous variation of the feed per tooth without a permanent overcharge of single blades can be achieved with a frequency according to formula (1).

$$f = \frac{n}{60} \cdot \frac{z}{z+1} \tag{1}$$

Figure 3a shows the movement of the tool teeth during a milling process with the mentioned parameters (feed rate of 500 mm/min, rotational speed of 5,000 rpm).

Figure 3b shows an example of the tool teeth movement with superposition of a vibration in milling direction by the AdSpin with a frequency of 62.5 Hz and an amplitude of 25 μm.

The feed per tooth amounts 33 μm without superposition. With superposition, it varies between 0 and 66 μm. The chip thickness would be modulated actively with the superposition of vibrations in feed direction. The effect on the emergence of chatter and the global stability limit with this superposition was verified in milling tests.
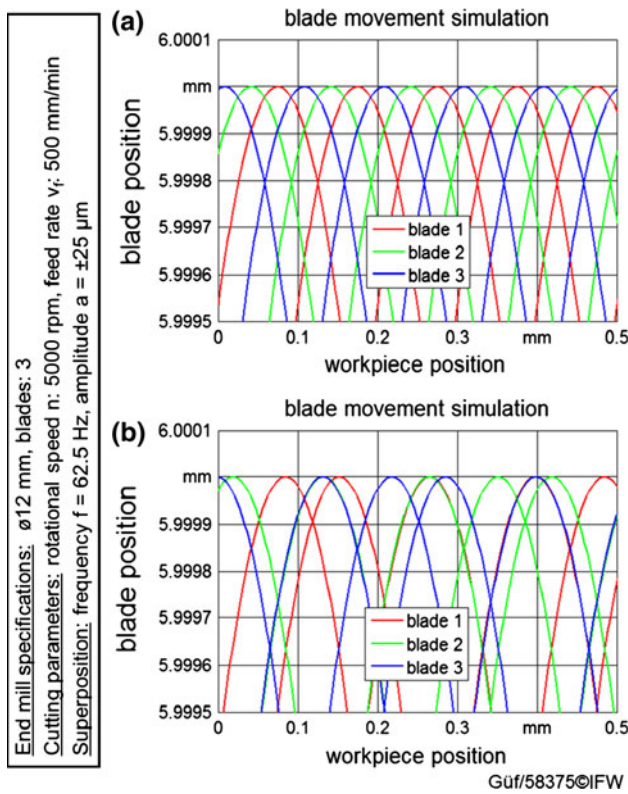
Fig. 3 Blade movement simulation without (a) and with superposition of a frequency in milling direction (b)

2.2 Experimental stabilization results

To verify the influence of the control of superposed vibrations on the stability of milling processes, the structure of the AdSpin was mounted to a three-axis milling machine in order to carry out milling tests (see Fig. 4).

The preliminary slot milling tests show, that by activating the superposition of the vibration (see Fig. 3), the process could be stabilized. During the milling tests, the tool vibrations orthogonal to the feed direction were measured with an eddy current sensor on a small aluminum hull, which was mounted on the end mill as a counter surface (see Fig. 4). To clarify the effect of active process stabilization, the control was switched off after 8 s at half of the workpiece. Figure 5 presents the magnitude and the frequency components of the tool vibrations.

It clearly points out the effect of the active process stabilization on the stability of the slot milling test. After switching off the control, the amplitude of the chatter frequency at 1,325 Hz rises significantly and the process becomes instable.

A different kind of surface finish was visible on the milled tool path. The moment the control was switched off, chatter marks built up on the surface finish. The analysis of the roughness shows that the surface quality decreases due
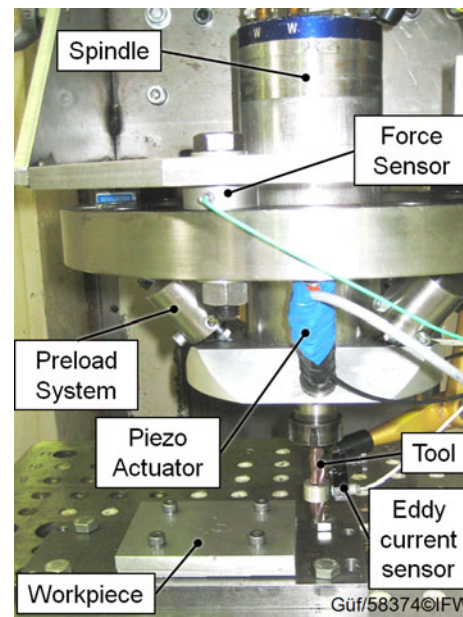

Fig. 4 Test set-up in a three-axis milling machine

to the chatter marks. The Ra value with control is Ra = 1.9 μm and without control Ra = 2.3 μm. The different surface qualities are shown in Fig. 6.

3 Analysis of the stability limits

In this chapter, the effect of the active process stabilization on the stability limits will be analyzed. Therefore, the compliance of the test set-up is measured and the stability limit for a slot milling process is calculated theoretically. Afterwards, the calculated stability limit is validated experimentally. The experimental validation is then
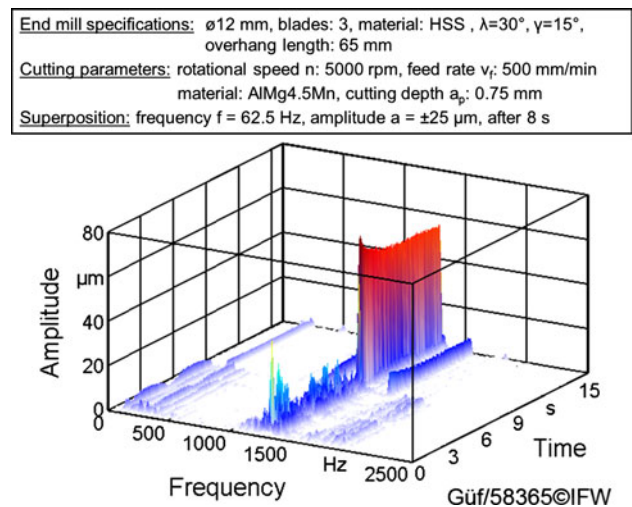

Fig. 5 Frequency analysis of tool vibrations normal to the feed direction during milling with control on and off
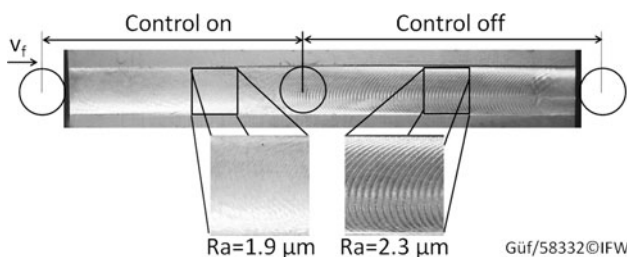
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489

Fig. 6 Workpiece quality with active process stabilization on and off

repeated with the active process stabilization to verify the effect on the stability limit.

3.1 Measurement of compliance of the test set-up

The tool tip was excited by an impulse hammer and the tool vibrations were measured by a triangulation sensor at the tool tip. The results of the measured compliance frequency response at the tool tip and the correlated model of a two-mass oscillator are shown in Fig. 7.

The measured compliance frequency responses for both directions are almost identical and show a dominant eigenfrequency at 1,340 Hz with a peak of about 28 μm/N (Fig. 7). It is assumed that this eigenfrequency is the first bending mode of the end mill.

In order to compare these results, the compliance frequency response is also measured at a spindle of another milling machine with the same end mill. The comparison of both compliance frequency responses points out that the first eigenfrequency and its compliance are almost equal. This confirms the assumption that the biggest compliance results from the tool.

3.2 Stability limit of the test set-up

Object of verification in this chapter is a slot milling process of Al7075 with the same end mill (diameter 12 mm,
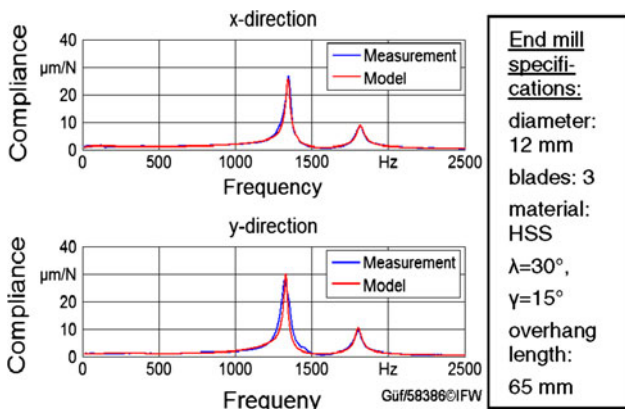
three blades, material HSS PM/F, $\lambda = 30°$, $\gamma = 15°$, overhang length 65 mm). The feed per tooth is $f_z = 15$ μm. This feed per tooth is conforming to the manufacturer instruction of the tool. To calculate the stability lobe diagram, the cutting force coefficients were adopted from [29] (tangential: Ktc = 794 N/mm^2, radial: Krc = 109 N/mm^2). With consideration of the identified model parameters, end mill geometry, cutting force coefficients and milling parameters, the stability limit was calculated for a slot milling process (Fig. 8). Due to the high compliance of the end mill, the stability limit only shows a globally stable cutting depth of about 0.05 mm. This results show that the calculated stable process range is very low.

To verify the calculated stability lobe diagram, a series of milling tests was performed. For certain rotational speeds, milling tests with a ramp-shaped increasing cutting depth were carried out. It was thereby analyzed at which depth of cut the milling process becomes instable. Therefore, the tool vibrations were measured with the eddy current (see Fig. 4). The process was described as instable when chatter occurred in the form of a dominant frequency close to of the eigenfrequency of the tool. The results in comparison to the calculated stability are shown in Fig. 8.

The calculated stability curve coincides roughly with the measurements. The deviations may result from a variation of the spindle speed during the milling process because the used spindle has no speed control. It comes to a slight loss of rotational speed during milling in dependency of the depth of cut. In addition, errors may occur from the simulation because of not exact known parameters.

3.3 Stability limit with active process stabilization

The stability of the test setup for a feed per tooth of $f_z = 15$ μm was determined in Sect. 3.2. To compare the enhancement of the stable process range with active

Fig. 7 Compliance frequency response at the tool tip of the test set-up
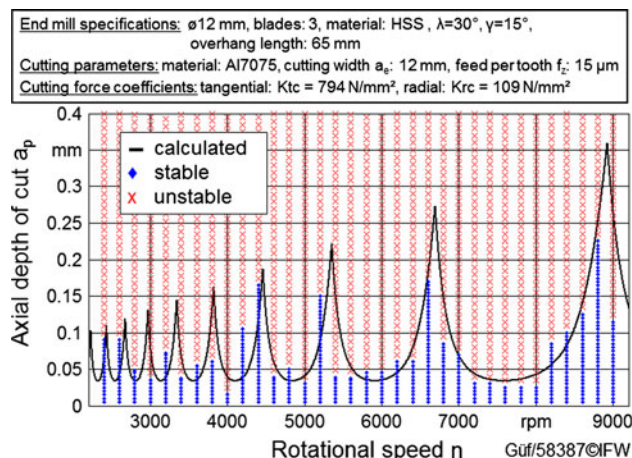

Fig. 8 Calculated and measured process stability

process stabilization by the adaptronic spindle system, the stability of the test setup was analyzed with active process stabilization.

In pre-tests other frequency formulas in addition to formula (1) were analyzed according to their stability increase. Thereby, only frequency formulas were analyzed, which varies the feed per tooth and alternately charged all blades, so that a single blade has not permanently a higher feed per tooth. It was verified that the following relation between the frequency f of the superposed vibration and the milling parameters (rotational speed n, number of blades z) show excellent stabilization ability:

$$f = \frac{n}{60} \cdot \frac{z-1}{z} \qquad (2)$$

In further milling tests, it was found out that by increasing the amplitude of this superposed vibration, the stable area could be shifted to higher cutting depths. To determine which stability limits can be achieved, the milling test to verify the calculated stability lobe diagram, described in Sect. 3.2, were repeated with the maximum amplitude of the vibration superposition. Figure 9 summarizes the achieved results of the active process stabilization.

A comparison of the stability limits without (Fig. 8) and with (Fig. 9) the active process stabilization clearly points out that especially the range up to 5,000 rpm can be stabilized significantly by the superposition of vibrations. In the speed range up to 3,000 rpm, the milling tests could be stabilized even to a cutting depth up to 0.8 mm. This represents an improvement factor of 16. In the range of 5,000 rpm and above, the stability could be also increased
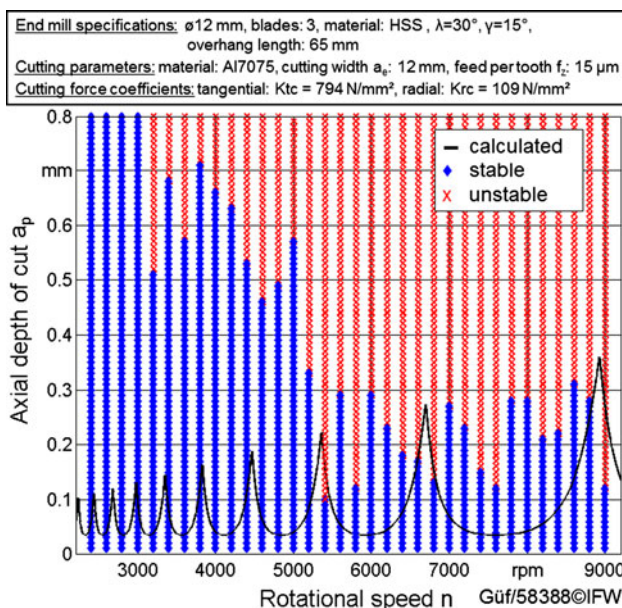
significantly at different rotational speeds compared to the tests without stabilization.

3.4 Analysis of process forces

In order to analyze the influence of the active process stabilization on the process forces, they were measured by the integrated force sensors of the adaptronic spindle system. Figure 10 shows the time signal of the process forces of a slot milling process ($n = 4,200$ rpm, $v_f = 189$ mm/min, $a_p = 0.1$ mm).

During the phase of material entry, the process became instable. After 17.5 s the process stabilization was activated. A vibration with a frequency of 47 Hz (according to formula (1)) and an amplitude of 70 μm was superposed to the feed of the tool. Figure 10 shows that the amplitudes of the forces decrease in the moment of stabilization activation.

The time-based frequency analysis of the force F_{fN} (Fig. 11) points out that the chatter frequency at about 1,325 Hz can be eliminated. Figure 11 also shows the influence of the vibration superposition on the process force F_{fN}, which is the highest force component in slot milling processes. The superposition generates an additional force with a frequency of 47 Hz and amplitude of 25 N. In comparison to the amplitude of the chatter frequency, this force is much lower.

The analysis of the milling forces showed that the modulation of the feed per tooth increases the milling forces in comparison to a stable milling process with a
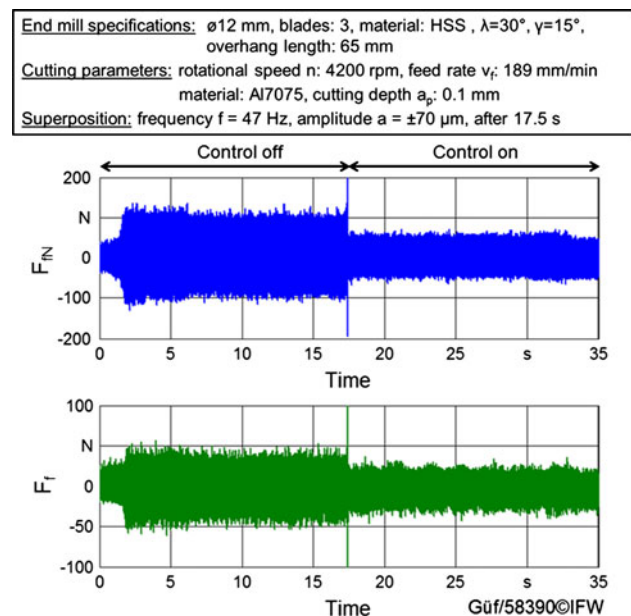

Fig. 9 Stability limit with the active process stabilization

Fig. 10 Process forces of a slot milling process with stabilization on and off

End mill specifications: ⌀12 mm, blades: 3, material: HSS , λ=30°, γ=15°,
overhang length: 65 mm
Cutting parameters: rotational speed n: 4200 rpm, feed rate v_f: 189 mm/min
material: Al7075, cutting depth a_p: 0.1 mm
Superposition: frequency f = 47 Hz, amplitude a = ±70 μm, after 17.5 s
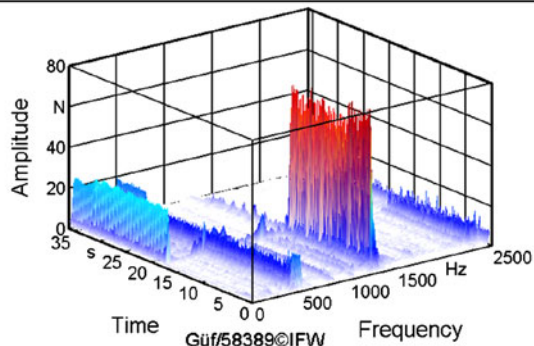
Fig. 11 Frequency analysis of the process force F_{fN} of a slot milling process with stabilization on and off

constant feed per tooth. But the higher load is distributed periodically to all edges.

4 Conclusion and outlook

Milling with long and slender end mills is a challenge with respect to an instable process and inaccuracy in the form of tool deflections because of the high compliance of the tool.

The AdSpin provides a good way to solve these challenges by improving the precision and productivity of a process. A tool deflection compensation, vibration damping and process monitoring are possible. Additionally, this paper presents the approach of active process stabilization. Due to the dynamic hybrid positioning of the tool in the range of 100 μm, the AdSpin offers a new way of an active modulation of the chip thickness. The generation of superposed vibrations in feed direction can disturb the regenerative effect and suppress the chatter appearance.

The active process stabilization was verified experimentally. It was shown that the presented approach can significantly improve the stability of a milling process with a long and slender end mill. Furthermore, the influence of stabilization on the process forces was analyzed. The stabilization creates an additional frequency force, which is very low in relation to the eliminated forces occurring at chatter.

The stabilization results should be transferable to other end mill geometries and materials. This has to be analyzed in further milling tests. The effect of the modulation of the feed per tooth on the wear of the cutting edges should be examined. Furthermore, analyses concerning the prediction of stability limits for the presented approach of stabilization are planned.

References

1. Neugebauer R, Denkena B, Wegener K (2007) Mechatronic systems for machine tools. Ann CIRP 56(2):657–686
2. Weck M, Brecher C (2006) Werkzeugmaschinen 3, Vol. 6., neu bearbeitete Auflage, Ch. 6 Prozessüberwachung, Prozessregelung, Diagnose und Instandhaltungsmaßnahmen, Springer, Berlin, pp 267–404
3. Altintas Y, Weck M (2004) Chatter stability of metal cutting and grinding. CIRP Ann Manuf Technol 53(2):619–642
4. Altintas Y, Brecher C, Weck M, Witt S (2005) Virtual machine tool. CIRP Ann Manuf Technol 54(2):115–138
5. Weinert K, Kersting P, Surmann T, Biermann D (2008) Modeling regenerative workpiece vibrations in five-axis milling. Prod Eng Res Dev 2:255–260
6. Denkena B, de Leon L, Grove T (2010) Prozessstabilität eines kordelierten Schaftfräsers. ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, Band 105(Heft 1/2):37–41
7. Weck M, Brecher C (2006) Werkzeugmaschinen 5—Messtechnische Untersuchung und Beurteilung, dynamische Stabilität, vol 7, neu bearbeitete Auflage. Springer, Berlin
8. Altintas Y (2000) Manufacturing automation: metal cutting mechanics, machine tool vibrations, and CNC design. Cambridge University Press, Cambridge
9. Brecher C, Esser M (2008) The consideration of dynamic cutting forces in the stability simulation of hpc-milling processes. In: Proceedings of the 1st international conference on process machine interactions. pp 7–14
10. Zatarain M, Bediaga I, Munoa J, Lizarralde R (2008) Stability of milling processes with continuous spindle speed variation: analysis in the frequency and time domains, and experimental correlation. CIRP Ann Manuf Technol 57:379–384
11. Smith S, Tlusty J (1992) Stabilizing chatter by automatic spindle speed regulation. CIRP Ann Manuf Technol 41:433–436
12. Sims N, Mann B, Huyanan S (2008) Analytical prediction of chatter stability for variable pitch and variable helix milling tools. J Sound Vib 317:644–686
13. Altintas Y, Engin S, Budak E (1999) Analytical stability prediction and design of variable pitch cutters. ASME J Manuf Sci Eng 121:173–178
14. Kern S, Schiffler A, Nordmann R, Abele E (2007) Adaptronische hybridgelagerte Motorspindel zur ratterfreien HSC-Bearbeitung. VDI-Berichte 1971:307–320
15. Ries M (2009) Aktive Motorspindel zur Unterdrückung von Ratterschwingungen im Fräsprozess, Fortschritt-Berichte VDI Reihe 2, Fertigungstechnik 670. VDI-Verlag, Düsseldorf
16. Denkena B, Bickel W, Ponick B, Emmrich J (2011) Dynamic analysis of a motor-integrated method for a higher milling stability. Prod Eng Res Dev 5:691–699
17. Drossel W-G, Wittstock V (2008) Adaptive spindle support for improving machining operations. CIRP Ann Manuf Technol 57(1):395–398
18. Rashid A, Nicolescu CN (2006) Active vibration control in palletised workholding system for milling. Int J Mach Tools Manuf 46:1626–1636
19. Abele E, Hanselka H, Haase F, Schlote D, Schiffler A (2008) Development and design of an active work piece holder driven by piezo actuators. Prod Eng Res Dev 2:437–442

20. Brecher C, Manoharan D, Ladra U, Köpken H-G (2010) Chatter suppression with an active workpiece holder. Prod Eng Res Dev 4:239–245
21. Hesselbach J (2011) Adaptronik in Werzeugmaschinen—Forschung in Deutschland. Shaker Verlag, ISBN 978-3-8322-9809-8
22. Denkena B, Möhring H-C, Will JC (2007) Tool deflection compensation with an adaptronic milling spindle. International Conference on Smart Machining Systems ICSMS, Gaithersburg
23. Will JC (2008) Adaptronische Spindeleinheit zur Abdrängungs- und Schwingungskompensation in Fräsprozessen. Dr.-Ing. dissertation, Leibniz Universität Hannover
24. Denkena B, Gümmer O, Sellmeier V (2009) Static and dynamic stabilisation of a milling process by an adaptronic spindle system for milling machines. Adaptronic Congress Conference Proceedings, Berlin
25. Denkena B, Gümmer O (2009) Enhancement of the static and dynamic compliance of a milling machine by an adaptronic spindle system. In: Proceedings of 9th international conference of the European Society for Precision Engineering and Nanotechnology, vol. 1. pp 333–336
26. Denkena B, Gümmer O, Will J C, Hackeloöer F (2008) Compensation of static and dynamic tool deflections during milling processes by an adaptronic spindle system. In: 2nd international conference of innovative cutting processes & smart machining, Cluny, Burgundy, France, 22–23 Oct 2008
27. Möhring H-C, Litwinski K, Gümmer O (2010) Process monitoring with sensory machine tool components. CIRP Ann Manuf Technol 59:383–386
28. Denkena B, Gümmer O, Will J C (2011) Adaptronische Spindeleinheit für Fräsmaschinen. Adaptronik für Werkzeugmaschinen—Forschung in Deutschland. Shaker Verlag, ISBN: 978-3-8322-9809-8: 343–363
29. Denkena B, de Leon L, Sellmeier V (2008) Impact of the tooth pitch on the process stability of milling. In: Proceedings of the 1st international conference on process machine interactions. pp 73–82