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*adaptive control,*
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Friedrich BLEICHER[1]
Paul SCHÖRGHOFER[1*]
Christoph HABERSOHN[1]

# IN-PROCESS CONTROL WITH A SENSORY TOOL HOLDER TO AVOID CHATTER

Hydro-, steam- and gas- turbines, aircraft components or moulds are milled parts with complex geometries and high requirements for surface quality. The production of such industry components often necessitates the use of long and slender tools. However, instable machining situations together with work pieces with thin wall thickness can lead to dynamic instabilities in the milling processes. Resulting chatter vibrations cause chatter marks on the work piece surface and have influence on the tool lifetime. In order to detect and avoid the occurrence of process instabilities or process failures in an early stage, the Institute for Production Engineering and Laser Technology (IFT) developed an active control system to allow an in-process adaption of machining parameters. This system consists of a sensory tool holder with an integrated low cost acceleration sensor and wireless data transmission under real time conditions. A condition monitoring system using a signal-processing algorithm, which analyses the received acceleration values, is coupled to the NC- control system of the machine tool to apply new set points for feed rate and rotational speed depending on defined optimisation strategies. By the implementation of this system process instabilities can be avoided.

## 1. INTRODUCTION

With the aim of optimising the mentioned instable machining processes, work piece and tool side sensors and actuators can be applied. Thereby, the application possibilities of sensors and actuators move closer to the process due to a progressive reduction of their size. Therefore, the use of sensory tool systems allows recording data of the machining process near the cutting zone and applying them for in-process control of process parameters.

This paper presents an active control system with acquisition of vibration data near the cutting zone via a sensory tool holder and the initiation of countermeasures to stabilise chatter processes on defined optimisation strategies.

[1] IFT – Institute for Production Engineering and Laser Technology, TU Wien, Austria
E-mail: schoerghofer@ift.at
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### 1.1. STATE OF THE ART

Regarding current technologies in the process monitoring, there are various companies and university institutions that have developed or are currently developing a wide range of solutions to measure and monitor machining data. Of the companies, three have been found to have similar aims in its methodology to record data and/or suppress unwanted effects such as chatter.

One product known as *Spike* (see [1, 2]), developed by Promicron Germany, reads machining data by placing its sensors directly at the tool holder with a battery operated, flexible circuit board set in epoxy resin. The measuring data is transmitted wirelessly to a receiver linked to a PC, ready for analysis in either real-time for in-process monitoring or offline use as a diagnostic tool. Whilst this measuring methodology is similar to the ideas presented in this work, a function to adapt both the feed rate and spindle speed for in-process control to avoid chatter vibrations is not included.

Another company that also incorporates chatter recognition is Komet Brinkhaus. Their product, named *ToolScope* [3], is a process monitoring tool that utilises both external and internal machine sensors to assist the machining process. The machining data is captured via Profibus and monitored directly from an NC program. One of its functions is the Adaptive Control (AC) module where parameters can be controlled, with chatter avoidance in mind. The methodology used here differs from the aims of the IFT since ToolScope comes equipped with internal sensors to measure its data and does not record data directly at the tool.

The company Okuma has also developed its own product, *Machining Navi* [4], for measuring and optimising cutting conditions. There are two types of this product that are worth mentioning. The first being *Machining Navi M-I*, it detects and suppresses chatter with pre-defined parameters; and the second, *Machining Navi M-GII*, suppresses chatter by controlling data captured over a microphone. Parameters can also be adjusted while monitoring the data. This system also poses differences to the aims of this paper as it also uses internal sensors and a microphone to capture the machining data rather than adapting existing tools with external sensors.

Another solution has been promoted by the IFQ from University Magdeburg where a MEMS acceleration sensor has been implemented in the tool shaft of a slim ball nose cutter for vibration sensing close to the tool tip. [5] Slender tools with small diameters have a limited possible installation space for the integration of electronics. Therefore, it is necessary to integrate sensors, energy supply and a data transmission system in different components near the tool. This approach differs from the presented work, in which all the electronics are integrated in the tool holder.

Outside of this project group, there are still other university institutions currently researching on similar topics. A research group called *"SmartTool"* [6, 7] headed by the TU Darmstadt along with several project company partners proposes similar ideas. Since October 2013, numerous initiatives have aimed to address problems of poor data collection and lack of robust data transfer in production processes, as well as lack of information transparency and networking. The concept of intelligent tools for the networked production of tomorrow aims to design a Cyber-Physical System (CPS) which consists of an intelligent tool system comprising of a tool holder with integrated sensors, and logic and transmission units to perceive production data. This tool system acts throughout the entire tool cycle and communicates information so that planners can reliably know the state and condition of the tool. Whilst the concept of *"SmartTool"* for sensor integration near the tool is similar to the ideas presented in this work, a real-time capable communication for an in-process adaption of machining parameters is not included.

The TU Munich is conducting a research project *"BaZMod"* [8]. It aims to develop an interface between its machine tool control and measuring instruments, actuators and intelligent tools equipped with process monitoring and optimising sensors. The final goal is to enable a standardization of data and energy exchange between the intelligent tool and machine control as each process has always been individually implemented by the manufacturer to date. This approach requires a specific spindle with an interface to the tool holder for data and energy transfer and, therefore, differs from the IFT concept.

The Leibniz University Hannover has also written a number of papers on similar topics. A paper recently published presents an approach for a monitoring and control system for tool deflection [9]. FEA methods were employed to determine the optimum positions of strain gauges on the sensory spindle slide with a control system implemented to maintain and measure tool deflection. This particular paper presents similar ideas of adapting existing spindles with external sensors to control and suppress an unwanted effect of machining. However, it distinguishes to the presented work, because of the concept to apply sensors in the machine tool and not on an independent component, e.g. a tool holder.

A second paper published in 2016 shows the results from the development of sensory tool holders for milling operations. In particular, focus is given on the optimal position of sensor placement on the tool for measuring of acting forces and temperatures during milling. It was concluded through simulations that sensor position generally depends on the considered directions of applied force. Future work will be dedicated to experimental verification of this topic. Placement of the sensor on the tool holder is an important point to consider and the results following this research may be relevant for future developments of the sensory tool holder developed at the IFT.

To sum up, several existing studies and products dealing with process monitoring and adaptive control to tackle the widely spread phenomenon of chatter. The unique characteristic of the presented work in comparison to existing solutions is the combination of a sensory data acquisition near the cutting tool, which is independent from the machine tool, and a real-time capable in-process adaption of machining parameters to initiate countermeasures in case of the occurrence of instabilities in the process.

### 1.2. APPROACH AND CONCEPT SOLUTION

Figure 1 shows the most vivid form of chatter, the so-called regenerative chatter effect. Self-excited vibration can occur by cutting of wavy surfaces, which are generated by the previous tool rotation. This has direct impact on the cutting depth. The crossing of small defects in the work piece surface can then lead to the destabilization of the milling process

[10]. To make the phenomenon completely understandable, more theories must be taken into account (location coupling, cutting force characteristics ...).

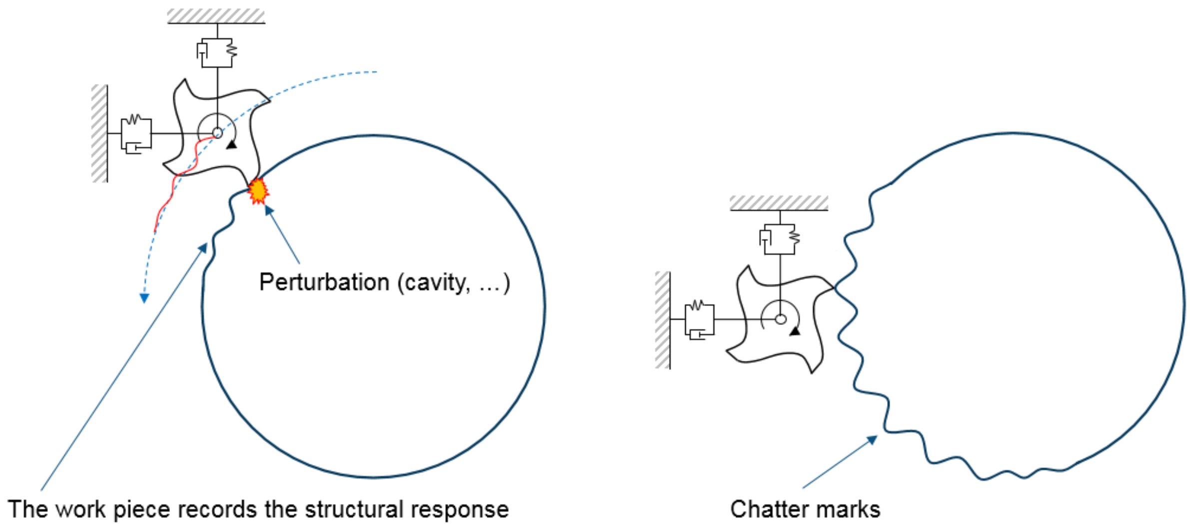


Fig. 1. Regenerative chatter [11]

In order to react correctly on instable milling processes, Fig. 2 has to be considered, which shows a stability lobe diagram. A stability lobe diagram depicts that specific combinations of spindle speed and cutting depth lead to instable machining processes, which can result in chatter vibrations.

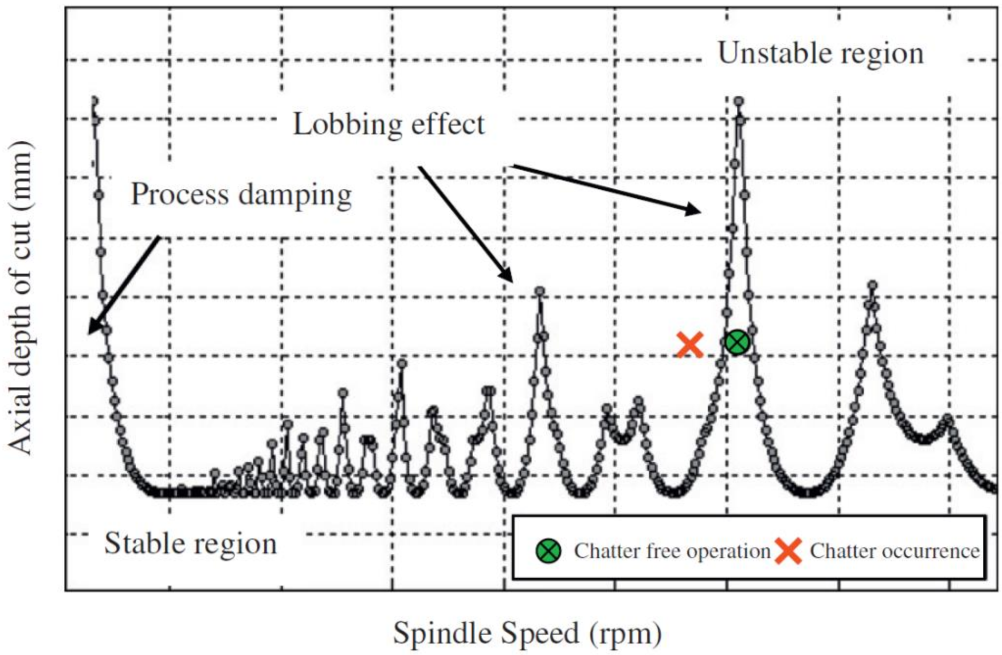


Fig. 2. Stability lobe diagram [11]

At high higher spindle speeds, a stabilizing effect due to process damping decreases, which causes a higher tendency for chatter processes. Process damping usually occurs at lower speeds and provides the stability due to the short waviness left on the work piece surface by high-frequency vibrations. This waviness in the surface interferes with the cutting tool flank face and dampen the vibration of the cutting tool [11]. This represented illustration of a stability lobe diagram does not show specific values for the axial depth of cut and the spindle speed. However, it describes the possibility to move the process out of instable zones into stable machining zones by reducing the feed rate or shifting of the spindle speed. Therefore, the research work focused on the parameters, feed rate and rotational speed to influence instable processes. The concept solution for the detection of process instabilities and the adaption of feed rate and / or rotational speed in the milling process and can be divided in the three following sections.

- sensory data acquisition near the cutting zone
- data processing and analysis (CMS – condition monitoring system)
- coupling of the NC system in order to stabilise the process by adaptation of feed rate or rotational speed

The first section of the concept solution is dealing with sensory acquisition of vibration data near the cutting zone. Thereby, a sensory system on the tool side should be considered. The data processing and analysis in the condition monitoring system (CMS) represents the second section. Algorithms, which are able to distinguish between stable and instable processes or to detect process failures, should be applied on an evaluation unit. Furthermore, the algorithms have to make the decision on how to adapt the feed rate and / or spindle speed in an appropriate way to influence the process. The supply of technological data about the tools, e.g. eigen frequencies could support the CMS in these decisions. Finally, the coupling of the CMS with the NC system in order to stabilise the process by proceeding new set points of feed rate and / or rotational speed to the NC system completes the concept solution as the third section. An implementation of a condition monitoring system in three different control systems (Siemens, Heidenhain and B&R) has been realized.

## 2. SENSORY TOOL HOLDER SYSTEM

In order to detect dynamic instabilities or process failures on the tool side near the cutting zone a sensor integration for a tool holder was developed. The approach for a sensor system integration at the tool holder is to gain more sensitive process information compared to e.g. the sensing of the spindle power and therefore, to be able to detect chatter vibrations at an early stage. For the first implementation, a capacitive MEMS sensor, i.e. microelectromechanical systems, has been chosen. This sensor was compared to a high quality three-axis accelerometer from the provider Brüel & Kjær in several experimental setups. As a result, the sensors showed a good compliance in the time signal and in the frequency spectrum for a defined excitation with a frequency of 100 Hz–3 kHz.

An analogue radio transmitter transmits the vibration data out of the rotational system to the receiver unit. The analogue radio transmission system operates at 433.92 MHz with frequency modulation. In order to not lose any of the vibration data through loss of digital data packages, an analogue transmission system has been chosen. Furthermore, the applied transmitter needs a lower constant current supply compared to several digital solutions. The total system consumption of one sensor and the transmitter is about 20 mA. Both, sensor and transmitter need a supply voltage of 5 V.

The whole measurement chain with its main components sensor and radio transmission system was implemented directly into a HSK A 63 tool holder. Figure 3 hows the final stage of the development process in the implementation of the sensor into the tool holder. Mounted on a circuit board and positioned in the rotational axis, the acceleration sensor measures the radial acceleration of tool holder vibrations. It was necessary to position the acceleration sensor in the rotational axis in order not to exceed the sensing range of the sensor due to the rotational acceleration caused by the spindle speed. Therefore, a relocation of the central position of the borehole for the cooling lubricant was required. By dividing this borehole into two smaller boreholes and positioning them around the slot for the circuit board, internal cooling is still feasible.

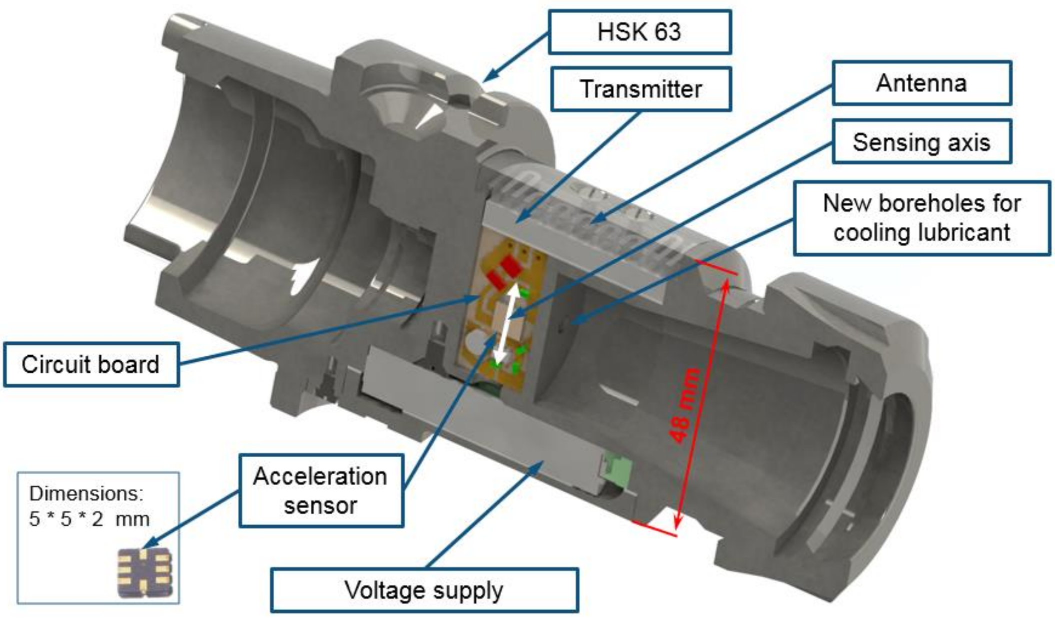


Fig. 3. Sectional view of the sensory tool holder

The transmitter and its cover with the implemented antenna in meander form was positioned diametric to the battery and the battery cover. Therefore, the sensory tool holder was constructed with focus on having the centre of mass as close as possible to the rotational axis. To balance the sensory tool holder, a G 2.5 class at 20000 rpm was utilised. The sensory HSK A63 tool holder is sealed and can be applied with cooling lubricant. Furthermore, the outer shape of the tool holder stays unchanged and, therefore, automatic tool exchange is possible compared to sensory tool holder solutions with e.g. an inductive data transmission system.

To power the sensory tool holder, a rechargeable solution was implemented. Via a recharge contact on the backside, the tool holder can be recharged in an external charging station. The rechargeable solution runs the system up to approximately four hours continuously. However, an on/off push button activates the tool holder just if it is inserted into the spindle in order to save run time of the battery when the tool holder is exchanged in the machine tool magazine.

Fig. 4 shows the result of an experimental test of the sensory tool holder HSK A63. Each of the curves in the diagram represent the frequency spectrum of a section of the vibration signal gained by the balanced sensory tool holder for milling at different rotational speeds from 1000 to 10000 rpm.

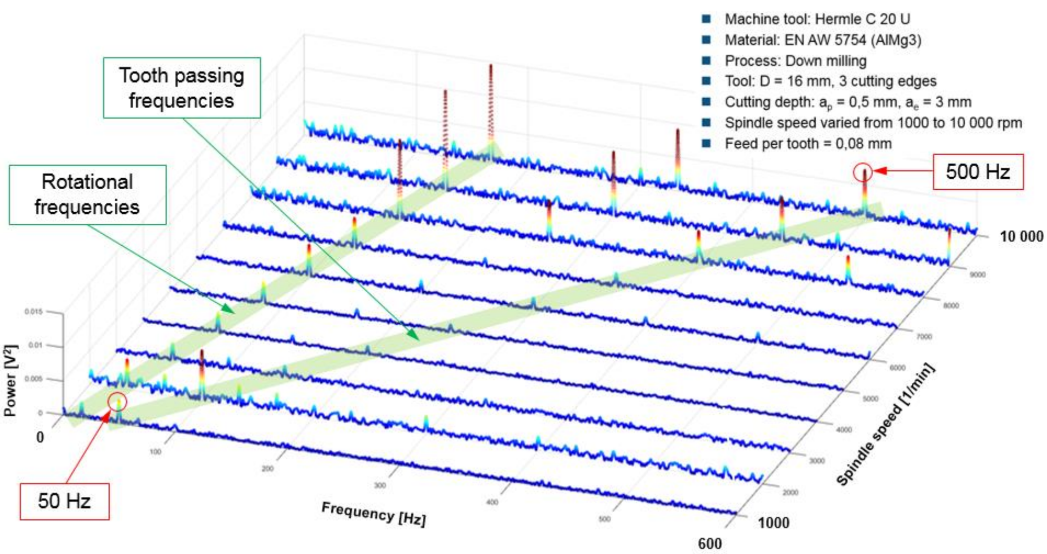


Fig. 4. Signals of the balanced sensory tool holder up to 10.000 rpm

A rotational speed of e.g. 6000 rpm conforms to a rotational frequency of 100 Hz. Multiplied by the number of cutting edges, which in this case is three, leads to a tooth passing frequency of 300 Hz. The experiment showed that up to a rotational speed of 10000 rpm, the correct detection of process vibration values can be achieved. The frequency peaks in-between the rotational and the tooth passing frequencies can be described as harmonics of the rotational frequencies.

Aside from applications in milling processes, the prevention of drill breakage or the detection of collisions could be areas of application for the achievements of this research work. Fig. 5 shows a result of a drilling experiment with the sensory tool holder.

The upper curve in this figure represents a stable drilling process whereas a new tool with a diameter of 3 mm in an Aluminium base body was used. It can be seen, that there are no significantly high peaks in the acceleration signal. In order to initiate a tool fracture, a steel pin was implemented in the work piece. The blue curve shows this process in which the tool broke at the interfering steel pin. The tool fracture leads to significant peaks in the signal. Also the following movement of broken tool is clearly visible in the signal.

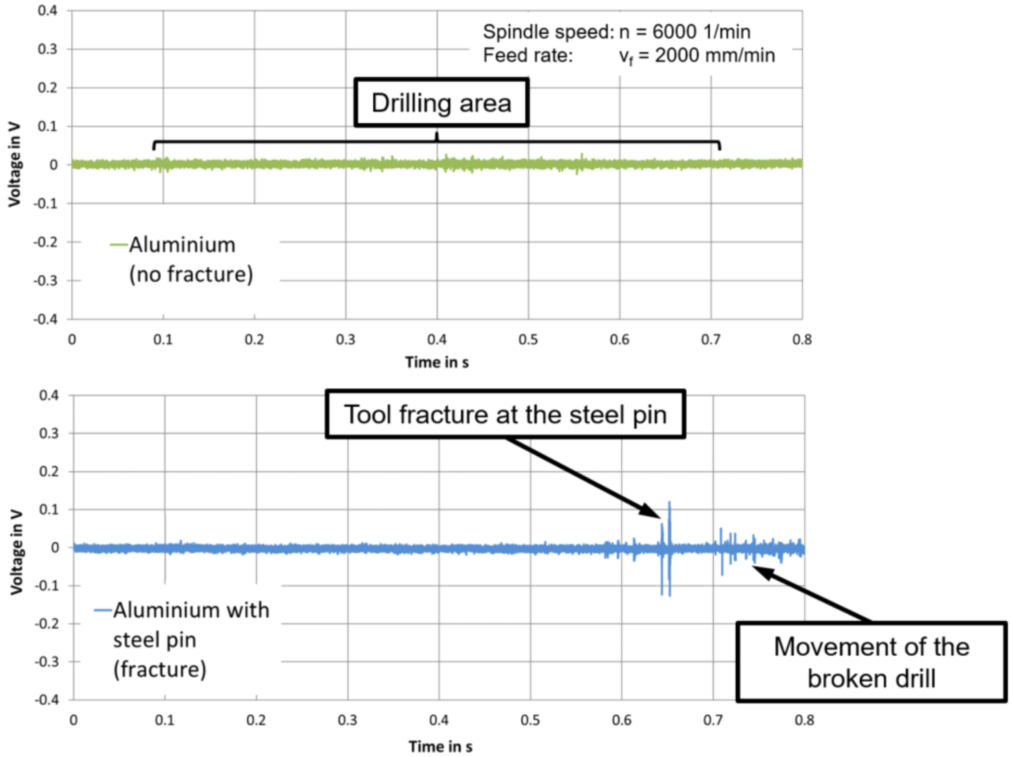


Fig. 5. Drilling in Aluminium (AlMg 3) with an interfering contour to initiate a tool fracture

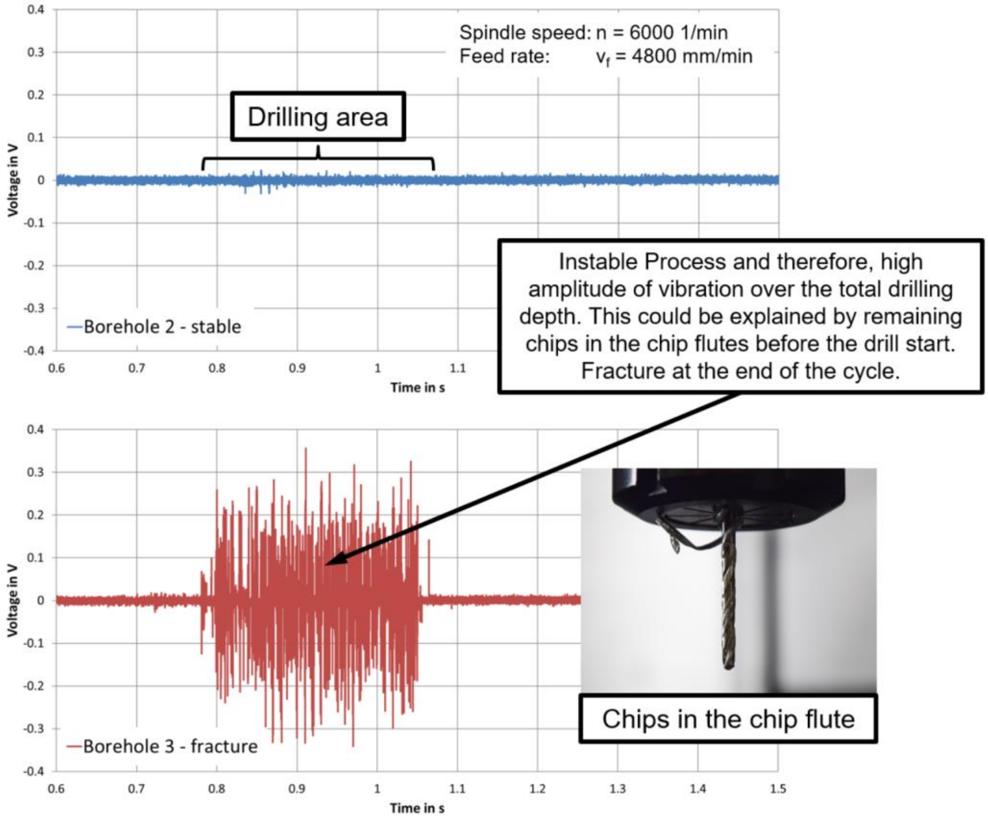


Fig. 6. Drilling in Aluminium (AlMg 3) until the occurrence of a tool fracture

A further experiment for the detection of drill breakage is illustrated in Fig. 6. In this experiment several holes have been drilled in an Aluminium work piece until a fracture of the drill occurred. The upper curve shows the acceleration signal of a borehole in the beginning of the experiment with a new tool. After several drilling operations, chips remained in the flutes of the drill as displayed on the right hand side of the figure. Therefore, the drilling process turned instable with significantly high acceleration peaks over the total drilling depth, which is represented by the red curve. As a result, the tool broke at the end of this drilling cycle.

These experiments show that instable processes and tool breakage of tools with a small diameter can be detected with the sensory tool holder. Therefore, this opens the opportunity for in-process-control to avoid tool breakage.

## 3. INTERFACES FOR A CONDITION MONITORING SYSTEM AND ADAPTIVE CONTROL

In order to initiate countermeasures in case of the detection of an instable process, a condition monitoring system needs to be coupled to the control system of the machine tool. As already mentioned, the IFT implemented condition monitoring systems to three different control systems.

Figure 7 displays one of these three test rigs on a Hermle C20U machine tool with an implementation of a Heidenhain iTNC 530 control system. The CMS is coupled to the control system via Ethernet and consists of three main parts, data acquisition hardware, a LabView Windows application with the algorithms for the data analysis and a software interface to the machine control system. The Heidenhain DNC (Direct Numerical Control) software interface delivers the RemoTools Software development Kit, which contains the COM components and the ActiveX control for integration in a development environment. [12]

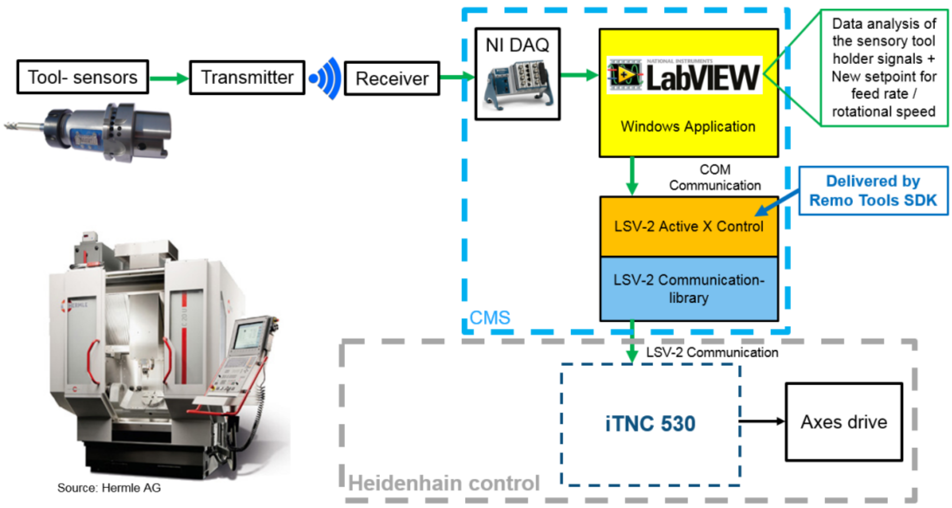


Fig. 7. Interfaces and data flow for a Heidenhain control system

The test rig represents the approach of an automated reaction of the machine tool based on vibration data of a sensory tool holder system.

An experimental set up with the sensory tool holder on the Hermle machine tool is depicted in Fig. 8. An aluminium block was clamped with an inclination of 45 ° in order to create milling paths in the shape of steps with continuously increasing cutting depth towards the end of the path. The reason for the step shape was to have the possibility to perform metrological investigations of the created surfaces after the experiment. In a previous stability lobe experiment with the same mechanical setup, it was possible to find rotational speeds where the process becomes instable at a certain value of cutting depth and significant chatter occurs. This rotational speed was then applied for an experiment with automated adaption of process parameters when chatter occurs. On the right hand side of Fig. 8, the analysed vibration signal from the sensory tool holder of two milling paths is displayed. The left signal curve shows the process stability when milling a path without interference of the process, i.e. without an adaption of process parameters. The second curve shows the process stability of a milling path with an automated adaption of feed rate and rotational speed as soon as the predefined, red coloured threshold for the defined level of process stability is exceeded. The curve shows that the vibration level lowers due to this optimisation strategy of parameter adaption. If this vibration level decreases further and falls below the green coloured readjustment border, the feed rate and the rotational speed increase again towards 100% of the initial values via a predefined ramp up. Therefore, the occurring chatter can be avoided. At about 27 seconds the tool leaves the work piece. Therefore, the tool loses the preload, caused by the contact to work piece. As a result, this leads to an excitation of the tool and a significant peak in the signal. All the developed test rigs for automated parameter adaption still give the operator the opportunity to reduce the feed and spindle speed values with the potentiometer.

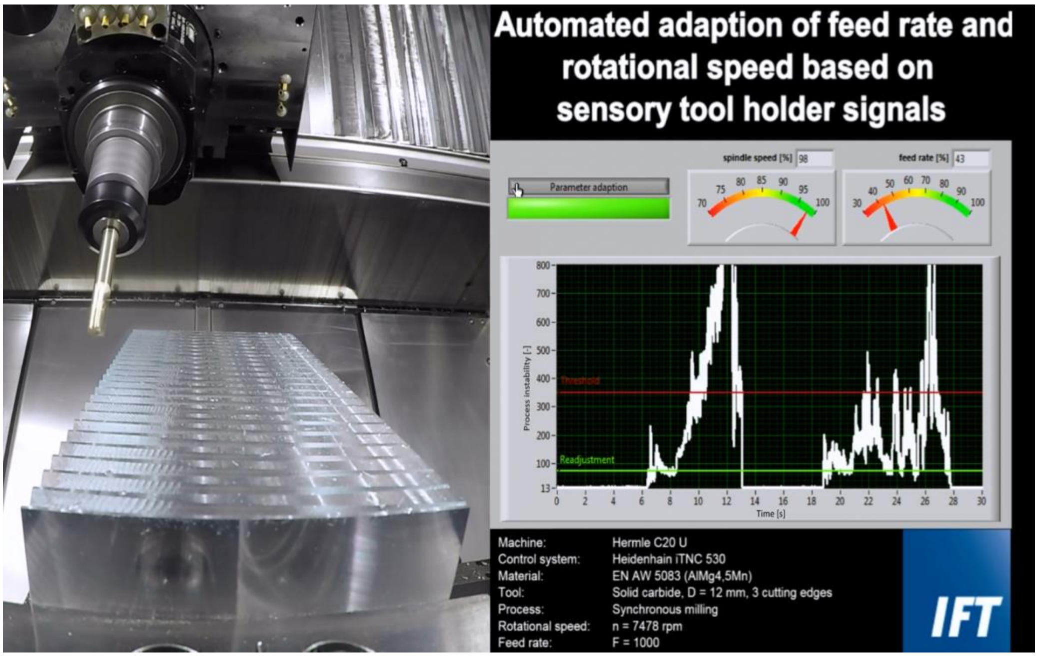


Fig. 8. Stability lobe experiment with automated adaption of parameters

## 4. SUMMARY AND OUTLOOK

The following remarks and findings can be summarised as a result of the project work:

- The approach of the presented and realised sensory system integration into a tool holder enables one to acquire process vibration data near the cutting zone.
- A condition monitoring system (CMS) analyses the received data of the integrated sensor system in order to detect process instabilities or process failures. However, this opens the opportunity for process documentation and monitoring.
- By coupling the CMS with the machine tool control system, countermeasures can be initiated to stabilise the machining process and thus, an in-process-control will be introduced. As presented in this work, the integration of condition monitoring systems was completed in three different control systems.

Due to the low price of the measurement components in the sensory tool holder, including the signal transmission, it represents an economic alternative to existing sensory tool holder systems. Furthermore, the shape of the developed tool holder is similar to common tool holder components, due to its compact construction without any additional interfering contours. Further technical and economic benefits for industry partners can be described by considering the potentials of sensory tool holder systems. First, data acquisition near the cutting zone gives the opportunity of gaining more sensitive process information compared to e.g. the sensing of the spindle engine power. Therefore, it delivers a database which can be used for process documentation or further investigations for quality management. Second, by applying sensory tool holders, a guide-system can perform process monitoring and give alerts in the case of a disturbance. Finally, the presented opportunity of in-process-control can lower production costs by reduction of throw-outs, especially in production of complex work pieces in small lot sizes.

Furthermore, the machining of composite materials with detection of the different materials and an automated adaption towards the appropriate parameters for the several materials can be a possible application of the project results. The analysed data of the condition monitoring system combined with the NC code could be forwarded to the company network in order to allow process documentation and process monitoring.

### ACKNOWLEDGEMENTS

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