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Production Monitoring based on Sensing Clamping Elements

Berend Denkena, Dominik Dahlmann, Johann Kiesner*

Institute of Production Engineering and Machine Tools (IFW), Leibniz Universitaet Hannover, An der Universitaet 2, 30823 Garbsen, Germany

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Abstract

Clamping errors in workpiece positioning decrease the production outcome of machine tools by causing rejects. An automated monitoring of these failures does not take place in practice, due to limited installation space for the sensor integration, especially in series production. Within the Collaborative Research Centre 653, the IFW develops and investigates a condition and process monitoring system based on sensing clamping elements in close cooperation with two industrial partners, the companies Roemheld GmbH (clamping technology manufacturer) and ReiKam GmbH (fixture construction service provider). It consists of hydraulic clamping elements with integrated sensors, decentral electronics for signal preprocessing, bus communication and a central processing unit. Measureable quantities are hydraulic pressure, the clamping stroke and the process forces. This article describes the prototypical realization and shows its usability in condition and process monitoring. Experimental results from measurements during milling operations and the comparison with a dynamometer demonstrate the performance of the sensory clamping system.

Keywords: condition monitoring; process monitoring; hydraulic clamping system; sensor integration; strain gauges

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1. Introduction

Clamping elements of fixtures hold the workpiece in a determined position in the working space of a machine tool. Therefore, positioning failures directly influence process behavior and machining results [1].

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* Corresponding author. Tel.: +49-0511-762-5210; fax: +49-0511-762-5115.
E-mail address: kiesner@ifw.uni-hannover.de

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To provide a reliable clamping, much research effort has been focused on computer aided manufacturing. A broad survey of recent research and trends in computer-aided fixture planning (CAFP) and design (CAFD) are given in [2-4]. Most of the CAFP/CAFD methods have the aim to determine accessible and collision free locations of fixture points that ensure part immobility under the application of external forces and moments. Boyle et al. conclude that many of the CAFD approaches have been tested for simple workpieces that are unrepresentative for industrial application [4]. On this account, despite the accurate effort in the phase of fixture planning and designing, malfunction or failure during machining cannot be excluded.

Nevertheless, to ensure a reliable and sustainable manufacturing, different developments were done to enable machine components to monitor the machining processes [5-7] and to interact with manufacturing processes by using mechatronic systems [8]. Nee et al. present a prototype of an intelligent fixture which improves machined workpiece quality by controlling the clamping intensity [9]. For the measurement of the clamping force, a direct sensing method with piezo-electrical force sensors is used. The direct monitoring methods can achieve a high accuracy, but due to numerous practical limitations, e.g. interferences with chips and cutting fluid, they are characterized as laboratory oriented techniques [10]. To enable suchlike applications in industrial environment, sensor systems are needed, that are more suitable for practical applications, at machine shop level.

Litwinski [11] presents an advantageous approach by integrating an intelligent sensor system into already existing components of a machine tool within the Collaborative Research Centre 653. His modular clamping system determines the potential use and performance of a manual sensory clamping fixture for machine tools, but considering the robustness it does not meet the requirements for industrial use yet. The system is characterized by integrated sensors for measuring cutting forces as well as accelerations and temperatures. The collected information allow conclusions on the current process state and the detection of process failures. Because of its performance for process monitoring the system is being transferred from research to industry within a joint research project. The main subject is the development and testing of a hydraulic clamping system with sensing capabilities for the use in series production.

This paper summarizes recent results of the project that enable monitoring of the fixture conditions and process forces. This includes the measurement of the hydraulic pressure, the clamping stroke and the process forces by the clamping elements themselves. At first, this paper gives an overview of the overall concept and then focuses on the integrated sensors of the hydraulic swing clamps. After that, a comparison between a dynamometer and a compound of sensing clamping elements demonstrates the applicability for the monitoring of milling processes.

2. Overview of the sensory clamping system

The development of the sensory clamping system bases upon a representative application scenario. It deals with the hydraulic clamping for multi-axis machining of cast casing covers. The exemplary hydraulic clamping fixture in Fig. 1a is an assembly that consists of a base plate with integrated hydraulic lines, three hydraulic swing clamps with appropriate supports and one hydraulic work support.

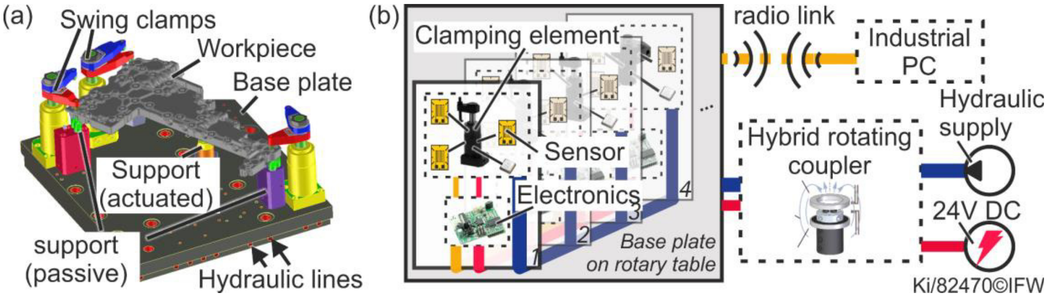

Fig. 1. (a) Hydraulic clamping fixture; (b) Overall concept for the sensory clamping system.

Fig. 1b summarizes the concept of the sensory clamping system. To provide the original hydraulic clamping fixture with sensing abilities, strain gauges and temperature sensors are applied to the clamping elements. Furthermore, the sensors are connected to electronic preprocessing devices that are integrated into the base plate. The direct proximity of analog sensors and digitizing unit shortens the susceptible analog transmission paths and offers the beneficial use of fieldbus communication at an early stage. By providing every clamping element with its own micro-controller device it is easily possible to expand the sensory clamping system by additional elements. A communication via a radio link and an inductive energy transmission substitute wired connections at applications with endless rotating tables.

3. Integration of Sensors

Because of the very low space consumption at the application point, strain gauges are suitable for compact integration at clamping elements. To point out the best positions for sensor integration, the deformations of the sensory clamping systems caused by the hydraulic pressure inside the piston chamber, external loads at the clamping arm and different piston positions are determined with finite element simulations (FEM). The used simulation model is shown in Fig. 2a.

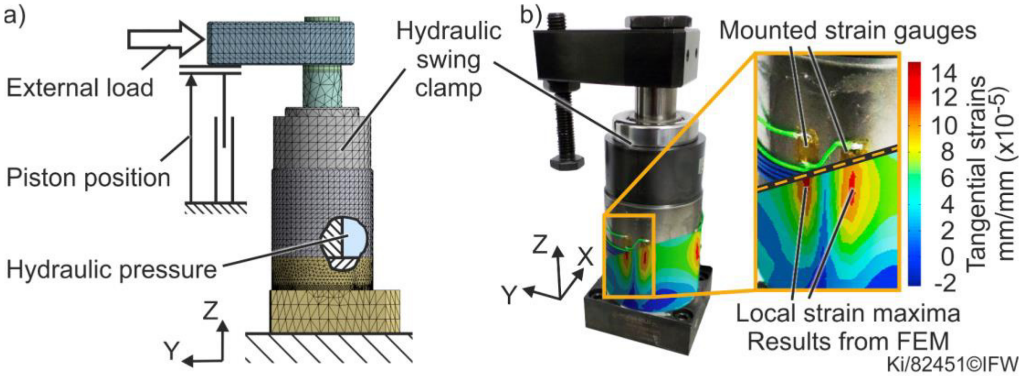

Fig. 2. Sensor integration based on FEM simulation.

By varying the different parameters of the simulation, e.g. loads and framework conditions, the distribution of strains changes and thus the positions of the local maxima. In Fig. 2b one exemplary result of the simulated strain distribution, which occur due to the increase of hydraulic pressure, is projected onto the clamping component to demonstrate the local strains maxima. For further results with more detailed discussions of the performed simulations see respective publication [12]. Based on the identified positions strain gauge sensors were applied at the clamping elements. The experimental verification and the potential use of these measurands for the industrial production is content of the following chapters.

4. Condition Monitoring

The following subsections demonstrate the abilities of the integrated strain gauges for the estimation of the hydraulic pressure inside the piston chamber, the piston position and external forces that are acting at the clamping arm. In addition, the integrated sensors are compared to common sensor systems. Furthermore, the relevance of these integrated sensing abilities is shown for the use for industrial praxis.

4.1. Hydraulic pressure monitoring

The main task of hydraulic clamping elements is the conversion of hydraulic pressure into mechanical clamping force. During the period of use, different error conditions, e.g. leakages at hydraulic connections and blocked-up hydraulic lines, arise and cause pressure differences in the hydraulics. Further error conditions occur by operating the hydraulic pump with incorrect parameters, e.g. excessive flow rates, often without even knowing it.

The integrated pressure sensitive sensors purpose the monitoring of the hydraulic supply of each sensory clamping element. Fig. 3a summarizes different scenarios that lead to clamping failures. If the flow rate of the oil exceeds the permitted setting, see red curve, impermissible pressure peaks occur. These lead to faster motions of the swing clamp and increases the load on the bearing of the piston and the swing mechanism. Insufficient pressure build-up is to be avoided as well, otherwise a sufficient clamping force at the start of the machining is not guaranteed. By monitoring the hydraulic pressure, faults can be detected and removed before serious consequences occur.

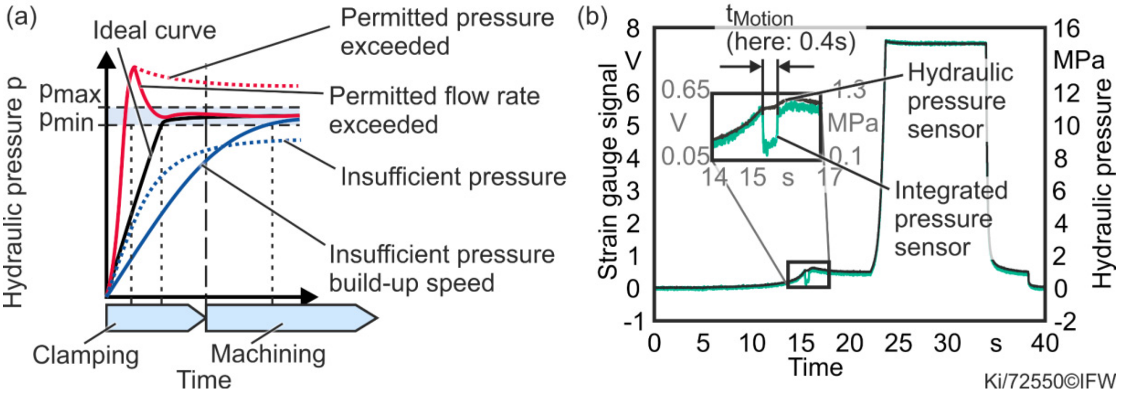

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Fig. 3. (a) Hydraulic pressure build-up scenarios before machining; (b) Measured signals of the integrated sensors at the swing clamp and a common hydraulic sensor at the hydraulic supply

The proximity is the crucial advantage of the integrated pressure measurement. Because of the acquisition directly at the clamping element, the integrated sensors measure the local pressure variations in the piston chamber. Even a momentary pressure drop during the stroke movement of the piston, see Fig. 3b, is detectable. The analysis of such effects, e.g. the duration of the drop, provides additional information of the wear condition of the piston guide. By use of a conventional pressure sensor near the hydraulic pump this information gets lost. Although, in the illustrated case example, the hydraulic line measures only 1.5 m between the pressure sensor and the clamping element.

4.2. Workpiece inspection

By the application and evaluation of strain gauges at different heights of the swing clamp cylinder, it is possible to extract information about the executed stroke. As a necessary precondition, the hydraulic swing clamp has to be in a stationary pressurized clamping situation, compare [12].

The position-dependent sensor signal components and the position of the piston follow a quadratic relationship. In order to use this relationship for measurement purposes, the characteristic curve was interpolated with a second order polynomial function. For the estimation of the polynomial coefficients, the experimental set-up in Fig. 4a has been used.

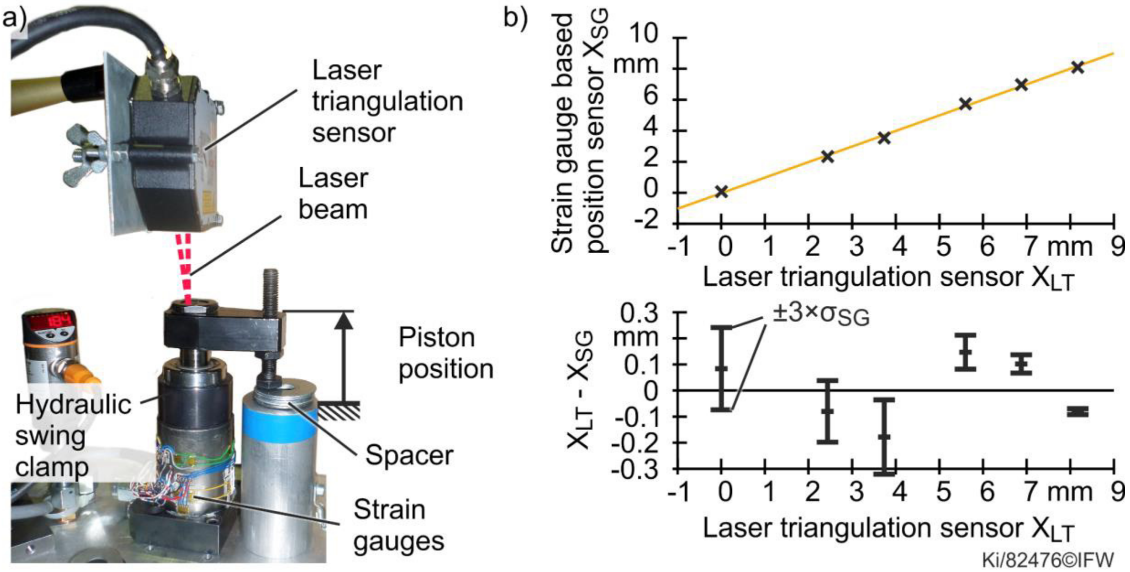

Fig. 4. (a) Experimental set-up to measure piston position at different heights; (b) Comparison of the measured piston positions with the integrated strain gauge sensors and the laser triangulation sensor

It consists of a hydraulic swing clamp with applied strain gauges for the position measurement and a laser triangulation sensor, which has an accuracy below 5µm. It additionally measures the absolute stroke as reference. By implementation the characteristic curve, the strain gauge based measurement of the piston position accomplishes a precision of approx. +/- 0.3 mm. The comparison of the integrated position sensor and the laser triangulation sensor is shown in Fig. 4b. Hereby, each of the standard deviations at different piston positions, which were varied with spacers at the clamping point, result from twelve clamping cycles.

Measuring the stroke of the clamping elements in a production system, e.g. inside a machine tool, is rarely done. Therefore, the space requirements of common measuring systems are often too challenging. Instead, small limit switches are used more frequently to test whether the piston has reached the desired end position or not. In those cases, the integrated position sensor system (strain gauges) has the following benefits: It consumes less space on the fixture then conventional position sensors and provides more information then limit switches, because it acquires intermediate stages as well. So, the sensing swing clamp has the opportunity to detect missing clamping points and interfering object by itself or otherwise to signal a properly executed clamping of the workpiece.

4.3. Detection of mechanical overloads

Forces that act at the clamping arm, e.g. clamping forces or process forces, apply bending loads to the swing clamp. The task of the strain gauges at the lowest level of the cylinder, see Fig. 5a, is the measurement of strains that are induced by the bending.

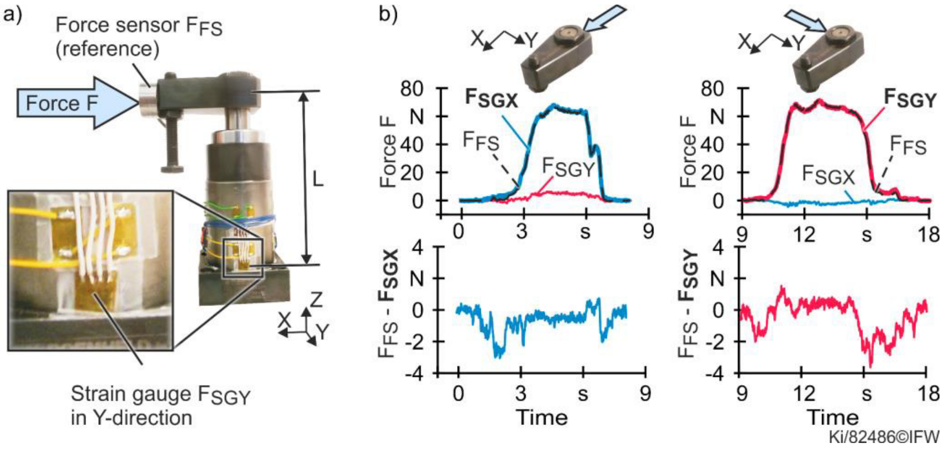

Fig. 5. a) Set-up for force application; b) Comparison between a conventional force sensor and the integrated sensors for force measurement

With the known lever arm L they are convertible into absolute forces. In the shown example, a horizontal force is applied sequentially in positive X- and Y-directions on the clamping arm. A conventional load cell measures the absolute values of the applied force of approx. 60 N, which corresponds to a simple press with the thumb. The diagrams in Fig. 5b present the measured force of the load cell (F_{FS}) and the integrated sensors (F_{SGX}, F_{SGY}) that measure the forces in independent directions. It is obvious that the integrated strain gauge based force sensors are able to detect the applied forces that act from different directions.

In addition, it is shown that even the variation of forces less than +/- 4 N can be detected with this measuring principle, despite the very robust and rigid construction of the clamping cylinder. Application potentials exist where the use of conventional force sensors are too expensive, not practicable because of the increase of the mechanical compliance or only feasible with great set-up effort, for example inside the working space of machine tools.

5. Process monitoring

This chapter deals with the assembly of the sensing clamping elements to a sensory clamping system. The first subsection describes the set-up in a machine tool. The subsequent section discusses results from utilizing a statistical envelope method in combination with the sensory clamping system for process monitoring.

5.1. Set-up inside a machine tool

According to the concept in Fig. 1, a sensory clamping system was realized that consists of a base plate with integrated hydraulic channels, three sensory swing clamps and one sensory support inside a milling center, see Fig. 6a/c.

The communication structure of the sensory clamping system, ranging from each sensing clamping element to the PC for central data processing, consists of the following two main paths. First, an analog connection links the sensors with the local signal-preprocessing device that is depicted in Fig. 6d. The micro-controller based device digitizes the signals from up to four strain gauge bridges and one Pt100 temperature sensor. These data is send to the processing unit over a CAN-bus (controller area network). The main advantages of this multi-master serial bus for the regarded application is the secure and fault resistant data transmission with only two wires and the good availability for embedded systems. A four-core cable suffices for enabling the digital communication and powering of the electronics and reduces wiring effort inside the machine tools working space.

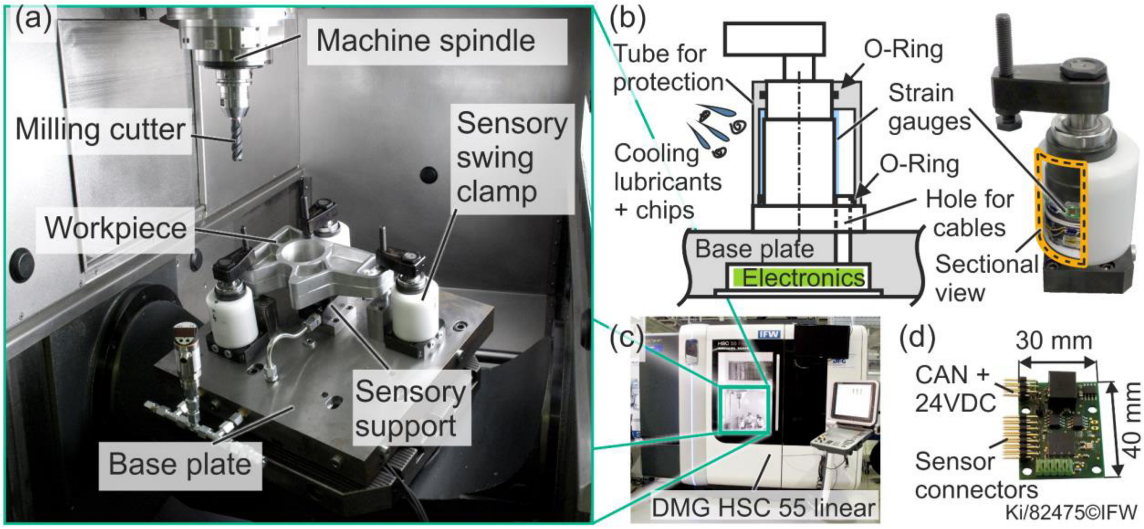

Fig. 6. (a) Sensory clamping system inside a milling center; (b) Protection of the sensors and the electronic devices; (c) Milling center for the milling tests; (d) Integrated electronic device for signal-preprocessing

For the use of the sensory clamping system in machining tools, the sensors and the electronics are protected against the harsh environmental conditions, e.g. cooling lubricants and chips, by a protective cover, see Fig. 6b. The analog cables are guided through a hole in the base of the clamping elements and connected with the electronic devices, which are also integrated and enclosed within pockets at the bottom of the base plate.

5.2. Monitoring with statistical envelopes curves

For the monitoring of milling processes several process monitoring methods exist. Industry oriented monitoring systems are often working with drive data from the machine control, e.g. electrical current of the spindle. This is a low priced solution, because no additional sensors are needed, but in order to measure process forces it has bad signal quality. On the other side, laboratory oriented measuring systems, e.g. measuring platforms, with high quality signals exist, that offer outstanding monitoring abilities. They are rarely used in industrial applications because of high purchase prices and the additional space requirement inside the machine tool. The sensory clamping system combines the advantages of process proximity to achieve better signal quality than the data from the machine control. Furthermore, it enables a more cost-efficient acquisition of process data than the use of measuring platforms. Therefore, the sensory clamping system is classified in a compromised manner between both extremal solutions, see Fig. 7.

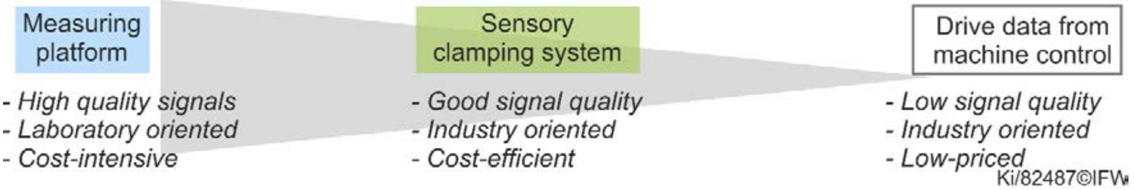

Fig. 7: Process data sources - Classifying the sensory clamping system

In the following, a method with statistical envelope curves, according to [13], is used to demonstrate the ability of the sensory clamping system in comparison to a measuring platform.

The aim of the experimental investigation is the detection of errors in the workpiece geometry. Therefore, an aluminum alloy probe was prepared with drilled holes. The probe is fixed on a three axis force dynamometer, which is clamped with the sensory fixture, see Fig. 8a/b.

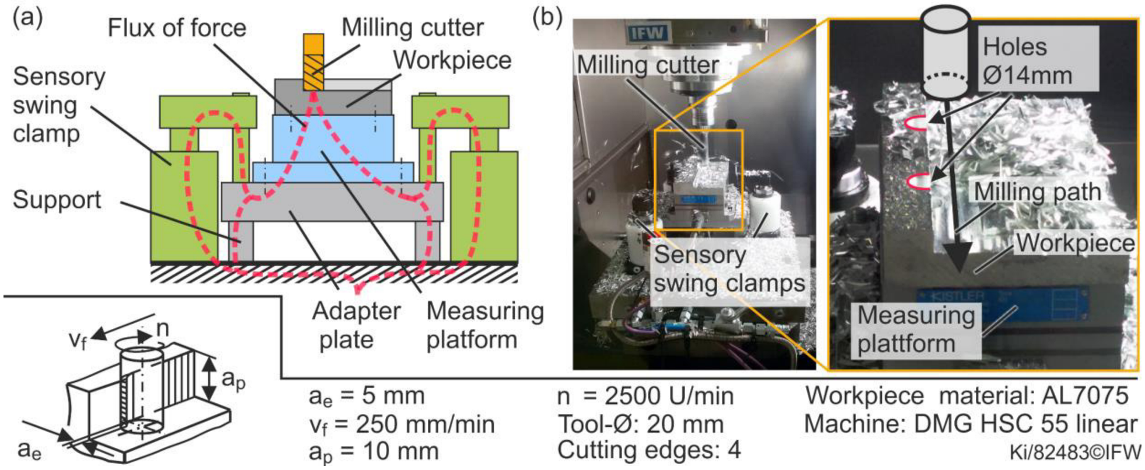

Fig. 8. Set-up for milling tests: (a) Schematic drawing; (b) Experimental set-up

During machining along the depicted milling path, the tool center point (TCP) changes its distance, respectively its levers arms, to every sensory swing clamp. This circumstance strongly influences the measured values of both force sensitive sensors of every swing clamp but rarely influences the three force signals of the dynamometer. Because of the resulting differences in the static signal components and in the number of signals, the measured data of both systems are digitally processed, as shown in Fig. 9a, to compute one monitoring signal of each system for the comparison.

First, a bandpass filter limits the bandwidth to a small range along the tooth engagement frequency. Then, the root-mean-squares (RMS) are calculated and smoothed by a lowpass filter with a cutoff frequency of 2 Hz. After that, the fusion of the individual signals is achieved by a summation. On the one hand, the merged signals offer the opportunity of a better noise to signal ratio. On the other hand, it reduces the six force sensitive sensors from the three sensory swing clamps and the three force signals of the measuring platform in each case to one signal. At the end, a zero-point adjustment is done.

To generate a first set of envelopes six similar milling paths without provoked errors were machined. With each additional data set the envelopes, which equal the 98 % confidence interval, tighten more around the expected value, see Fig. 9b. To retain the overview, only the last three envelopes are illustrated.

It is observable, that the distance between the monitoring limits and the expected values of the measuring platform is smaller than the distances of the sensory clamping system. This results from 500-4000 times higher signal to noise ratio of the measuring platform. Consequently, using the measuring platform higher sensitivity to monitoring faults is achievable. Fig. 8a illustrates the reason for this differences in signal qualities that result from the flux of force additionally to the disparity due to the price classes. Considering the set-up, it is obvious that the whole flux of force, from the TCP to the adapter plate, passes the measuring platform but then is divided up among the non-sensory supports and the swing clamps with the integrated force sensitive sensors. Nevertheless, both systems are able to detect the introduced failures, the drilled holes with a diameter of 14 mm. Therefore, both systems indicate similar time intervals with crossed monitoring limits, see Fig. 9b.

In contrast to the dynamometer, the sensory clamping system has a further decisive advantage, regarding the application inside a machine tool. The clamping elements are essential component of a machine tool for the machining, because they fix the workpiece in a defined position. The measuring platform is not. It is a disruptive element that consumes valuable working space inside the machine tool, without having any further functionalities but the force measurements.

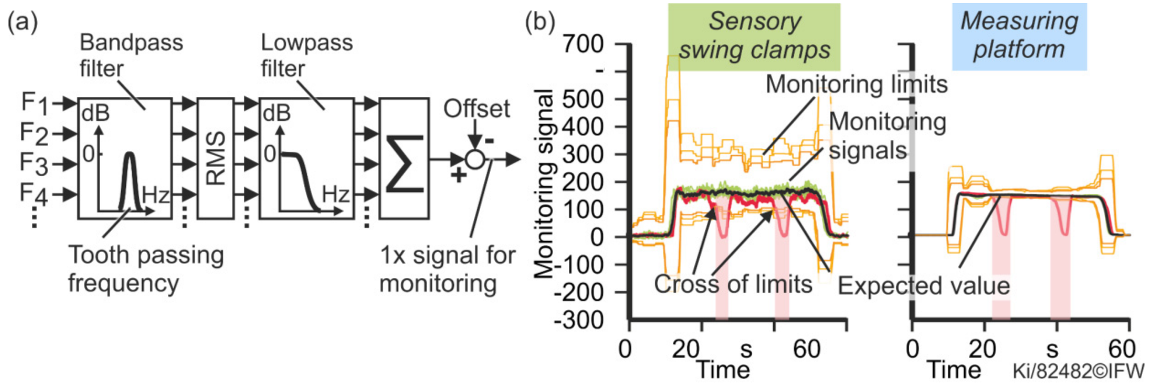

Fig. 9. (a) Estimation of the monitoring signal from dynamic process forces; (b) Comparison of monitoring results

6. Conclusion and Outlook

The presented paper shows latest results from the development of a sensing fixture for the use in an industrial environment. At first, a general overview of the system structure and the description of the fixture design are given. To provide the hydraulic clamping elements with sensing capabilities, the positioning of strain gauges based on estimated strain distributions from FEM simulations. The integrated sensors enables the indirect measurement of hydraulic pressure, acting forces and piston position. Investigations with experimental set-ups exemplarily verify the usability of a sensory hydraulic swing clamp.

Afterwards, the realized set-up of the sensory clamping system for the clamping of workpieces inside machine tools for milling is introduced. It consists of sensing clamping elements with appropriate, decentral processing devices. At the end, the ability of the sensory clamping system for process monitoring is discussed in comparison with a measuring platform. As a laboratory oriented measuring system, the measuring platform has a better signal to noise ration. However, for the use in industrial applications, the sensory clamping system has decisive advantages concerning purchase costs and applicability.

The further development of the condition monitoring approaches using the integrated sensors is subject of future research. The aim is to reveal extensive information, e.g. about the swing movement of the clamping arm, by utilizing further monitoring methods such as pattern recognition during the clamping procedure. For this purpose, the fusion of the different measuring quantities of the integrated sensors provides potential for improvements.

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