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Feasibility test of a flexible PCB with embedded strain gauges to measure cutting forces on the tool holder

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Abstract
The variety of product demand is increasing day by day in industrial applications. It also aims to make products with higher quality and low lead time by considering safety issues. In addition to these demands, the decreasing number of operators in manufacturing makes the emergence of self-managed machine tools in the industry inevitable. Despite CNC machines' high accuracy and precision, solutions to process-related problems such as vibration and tool wear have recently become the subject of machine tool manufacturers and researchers with the development of control and sensor technologies. The limited tool and machine tool rigidity can cause defects in manufactured parts, which may lead to parts being scrapped, increased production time, and safety problems. In all these aspects, force-measuring cost-effective smart tool holder sensors can play a major role in increasing the productivity of the machining process.
Many studies in the literature have shown that knowledge of cutting forces plays a key role in solving these problems in milling. Therefore, a plug-and-play, easy-to-manufacture flex PCB-based design with semiconductor strain gauges in full bridge configuration is explored in this study. Shaker excitation tests were applied to evaluate the applicability of the design. The study revealed that semiconductor strain gauges mounted on flex PCBs provide the potential to be employed in smart tool holders, which have an important part in the development of the digital shadow of the machine tool.

Digital Twin, Machine tool, smart tool holder, chatter, milling.

1. Introduction

As it is currently being experienced, the manufacturing industry getting through the fourth industrial revolution these days. The main idea is to interconnect and communicate value-adding assets to each other and process digital data to obtain higher added-value products. By using cutting-edge technologies in communication, sensor, and computation fields, it is expected to have higher demand to increase this solution all around the world.

In CNC Milling, several studies provide the solution for the digitalization of the process. The process outcomes of milling are mainly vibration of the tool and workpiece, tool wear, and tool deflection, which make cutting forces the principal determining factor for the dynamics of the process and may result in undesired surface quality [1].

The sensor and information technology development gained some potential in the knowledge of the in-situ process physics to improve part quality. At this point, sensory tool holders bring some advantages about knowing the real-time part quality estimation [2]. However, the commercially available products and academic studies show a need for high-resolution and bandwidth sensors without compromising the stiffness of the structure.

Kistler's 9170B model consists of 4 piezoelectric sensors that measure the forces in the X, and Y directions and the moment in the Z direction. It samples 10 kHz up to 16000 rpm. However, its cost restricts its use in regular production [3] and, this product is most suitable for laboratory measurements. Another product is Pro-micron's Spike Wireless model, which consists of strain gauges measuring in 4 different directions (M_x, M_y, M_z, and F_z) Chatter and tool wear detection can be done. It can measure at 2.5 kHz up to 18000 rpm, which has a relatively low bandwidth for high-speed milling applications [4].

Academic studies have shown that higher precision results can be obtained. In the study of Xie et al. [5] with 4 capacitive sensors (F_x, F_y, F_z, and T_z) with a sensitivity of 5-10 mV/N was achieved. The BT50 tool holder has been modified to increase accuracy and the stiffness has been lowered. In a similar study, Rizal et al.[6], achieved higher sensitivity by integrating 24 strain gauges over the intermediate sensing element into the SK40 tool holder, which increased the overhang distance, and lowered the stiffness. In the study of Zhan et al. [7], strain gauges with higher gauge factors were used. The BT40 tool modified the holder by removing some material and compromising stiffness.

KU Leuven has already shown an instrumented tool holder to measure cutting forces with wireless data and power transmission [8]. This study improves upon the previous one with a simple design while promising higher sampling rates and resolution. In section 2, the design of the sensory tool holder is described. In section 3, static and dynamic testing results are explained. The summary, conclusion, and future studies are discussed in section 4.

2. Design of Sensory Tool Holder and Test Setup

In the presented design, four semiconductor strain gauges from two Wheatstone full bridges are used on the HSK-32 tool holder (ER collet type, Haimer) to measure bending in two perpendicular directions (refer Figure 1 for M_{B1} and M_{B2}). The strain gauges are first glued on a flex printed circuit board (PCB) to simplify the design. Gluing the strain gauges to a flex PCB

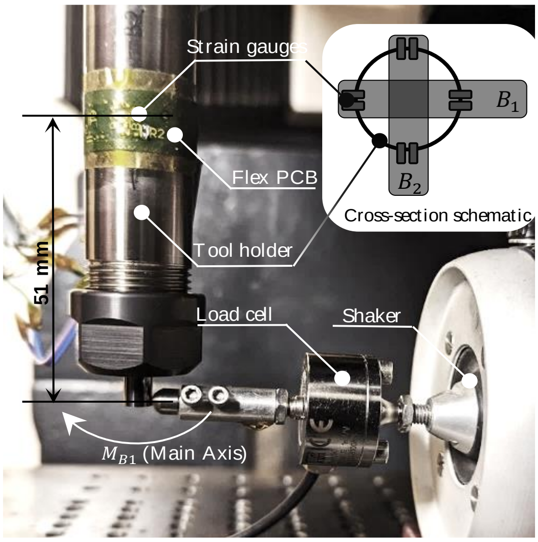

Figure 1: Flex PCB with strain gauges glued on the tool holder body. Test setup to measure sensitivity and frequency response can also be seen.

reduces the number of parts and assembly steps. Precision gluing of the PCB is made possible by roll transfer method.

The flex PCB strip with strain gauges was glued to the tool holder by curing with resin, which takes almost two days of work. A precision roller is designed to avoid residual effects of the strain gauges during the placement of flexural PCB on the tool holder. Micro Instruments (SS-060-033-500P) semiconductor strain gauges with gauge factor 140 (±10) were used, due to their small size (standard package: 0603). In the shown setup the gauges are calculated to have a bending sensitivity of approximately 3.19 (±0.22) mV/Nm.

4. Test Results

Tests were done in line with ISO 230, by using an electromagnetic shaker excitation (refer to Figure 2) with a sine sweep test between 30 Hz to 5000 Hz, and the data was digitized at 25 kHz by NI DAQ at 24 bits. The signal was also filtered at 10 kHz with an anti-aliasing filter. The tool holder was held in the DMG Sauer US20 machine. The load was applied to the 6 mm tungsten carbide cylinder held with a 7 mm overhang. The applied load is measured with an HBM U9C load cell.

The sine sweep results are shown in Figure 2. It can be seen that the two bending directions show high orthogonality (~6% cross talk). At higher frequencies, the coherence between the input and output drops to an unacceptable level. At higher frequencies, it was observed that the input force spectrum also drops (not shown), rendering 3000-5000 Hz not useful. Nonetheless, the sine sweep results are valid until 3000 Hz.

The assembled system's measured quasi-static sensitivity (~3 mV/Nm) is lower than the previous design [8]. It is recommended that a high-resolution ADC is employed to digitize the signal from the proposed design as compared to 16 bits in the previous one.

5. Summary and Conclusion

This work presents a flex PCB-based design for instrumented tool holders to measure the cutting forces. By applying a sweep shaker excitation test between 30-5000 Hz, the characterization of the design is obtained. The input and output signals showed a small cross-talk with high sensitivity. Thus, the result shows that the placement of the strain gauges on the flex PCB presents a promising alternative to previous designs.

This sine sweep test also shows that the parameterized FRF can be used to obtain cutting forces up to 3000 Hz. The effect on structural dynamics should be filtered out and the model of the cutting tool should be added using methods like receptance coupling as mentioned in [9].

In the future study, this way, by adding the wireless data acquisition system (24-bit digitization is recommended) and translational and torsional load sensors the real cutting force and torque can be measured so that the real-time process quality estimation can be done on the machine tool to reduce the time spent on the metrology of the parts [9]. The test is all conducted in a dry environment. Therefore, for wet machining, a balanced waterproof casing is required.

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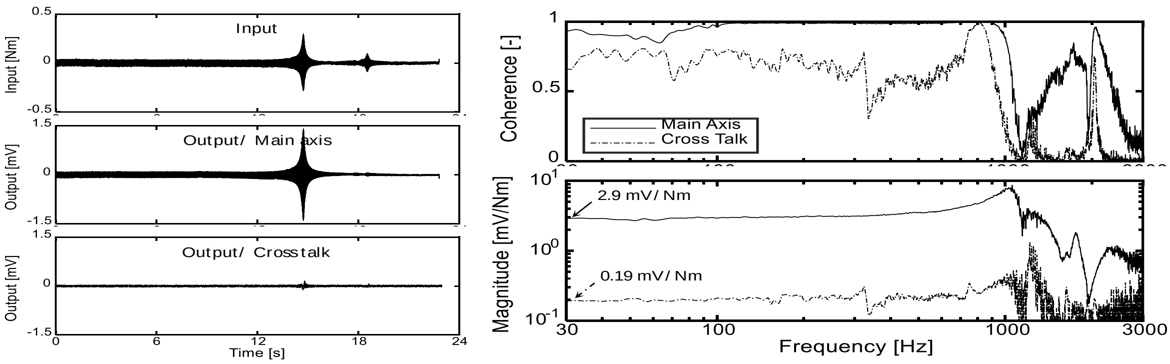

Figure 2: Sensitivity test results, counter clockwise from top left: applied bending moment, output of the main axis, output of the cross talk (all in time domain), frequency response function, and coherence.