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A COMPARISON BETWEEN ON-AXIS AND OFF-AXIS MEASUREMENTS DURING MACHINING OPERATIONS

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Abstract. *With the recent push towards Industry 4.0, gathering information from the machine tools becomes a necessity in order to create a smart factory and therefore maximize the efficiency of the production process. One parameter especially useful during turning and milling operations is the spindle vibration, which can indicate the quality of the surface finish of the workpiece, the level of effort for the current operation, possible defects in the bearings that can lead to machine breakdown, among others. Having a constant stream of data during machining operations allows the user to be warned about possible problems during operation and therefore to perform predictive maintenance, increasing the uptime of the machine and reducing the chance of wasting materials due to low-quality finishes. This article proposes two methods for measuring spindle vibrations: (i) from a static position, e.g. close to one of the spindle bearings and (ii) using a wireless data transmission system with sensors placed directly on rotating parts. During the operational measurements, the cutting forces are constantly measured by a dynamometer mounted on the tool holder. The level and severity of the cutting forces are then analyzed against the signals coming from the rotating part and the static accelerometers. The wireless data transmission system, developed in this framework, uses strain gauges as primary sensors, process the signal and send it optically to a stationary receiver, which then transmits the data for further analysis. The static measurement is performed with accelerometers that are directly linked to the data acquisition system.*

Keywords: *Industry 4.0, telemetry, strain, torque, vibration.*

1. INTRODUCTION

Monitoring of cutting processes is very important to achieve consistently good surfaces on the produced parts. As machine tool operators in high productive series production work on different machines at the same time, ideally, each of these machines should perform the monitoring itself. In view of the Industry 4.0 framework (Sendler, 2013), machines and other industrial equipment (e.g. robot manipulators, transportation systems, etc.) should be able to communicate among each other and, even, make decisions.

The continuously monitoring of the machine condition allows, for example, predictive maintenance and avoiding unpredicted machine stops (Dimla, 2000; Teti *et al.*, 2010; Zhang *et al.*, 2016). An automatic chatter detection scheme, that uses the same set of sensors, can feed information to the machine CNC or serial robot control. Other benefits of continuously monitoring the machining conditions include the assessment of typical machine cycles, detection of misuse (crashes, overloads, etc.), the monitoring of energy efficiency that is an ever-increasing demand in the field (Ruiz *et al.*, 2015), etc. Moreover, the gathering and use of multiple operational parameters has gained renewed interest in the context of Industry 4.0 (Sendler, 2013), a framework for integrating machine users, manufacturers and other players in the supply chain, which is based on the availability of some machining parameters over the internet.

To obtain experimental data on the many machining parameters, such as cutting force, speed, feed, axis vibration and tool condition, it is necessary to install sensors in key positions so that those variables can be properly measured. These sensors can be installed in the tool post (Yaldız and Ünsaçar, 2006), in the bearings holding the spindle or in the spindle itself, using brushes or wireless communication to send the data back to a computer (Elnady *et al.*, 2012). The range of sensors that can be used in this scenario includes, among others, accelerometers, dynamometers, load cells and strain gauges, which measure, directly or indirectly, vibration levels, forces and strain/stress that occur during the machining operation.

A benefit that can be gained from continuously monitoring the machining conditions is detecting defects on the machine, tool wear and other problems that could affect the quality (surface finish, dimensions, etc.) and would require the machine to be temporarily deactivate for maintenance (Dimla, 2000; Teti *et al.*, 2010). If those flaws are detected early, the operation of the machine tool could be interrupted briefly for maintenance, reducing the time wasted with breakdowns and avoiding the waste of energy and material.

This paper presents an innovative system that allows for sensors to be placed on a rotating part such as a spindle and their data to be read in real time, in order to better control this system.

2. PROBLEM STATEMENT AND CONCEPTUAL DESIGN

The work presented here is under a broader scope that aims at including a network of sensors on machine that can perform a set of tasks, which may include the monitoring of: structural health/integrity, process quality, energy consumption, etc. The task described in this manuscript focus on enabling sensors to be mounted on moving parts, more specifically, rotating shafts, which is a technically challenging task when it involves transferring power and data, to and from the sensor. Historically, slip-rings have been used for that matter, with the known disadvantage of being susceptible to noise, electromagnetic interference and not being reliable for long periods of time, due to wear. A set of possible solutions rely on wireless transmission of data as, more recently, such transmission apparatus became available (Bamberg *et al.*, 2008).

Although it is possible to monitor the conditions of a bearing, for example, via stationary accelerometers, assessment of torque load on the same shaft is not that easy. In order to measure the conditions of a rotating axis, without actual contact between the rotating sensor and the stationary conditioning/processing electronics, there needs to be a form of wireless communication. That way, part of the signal conditioning would still be mounted, together with the sensor on the rotating axis, while the acquisition system's bulk should be placed in a stationary position near the machine.

In order to investigate the feasibility of such a measuring device, a torque measuring system is proposed which uses two bi-axial strain gauges, placed on opposite sides of the shaft and wired to be sensitive to torque, while keeping cross-sensitivity to transverse shear and bending moment as low as possible. In this context, the shaft represents a machine tool spindle, which is directly linked to the workpiece and, therefore, is subject to the same torque as the latter.

For this experiment, the full bridge assembly of strain gauges needs to be powered and the output signal amplified and sent back to the acquisition system. This task is performed on-board of the shaft by an Arduino Uno board, selected due to its availability, cheap price, small size, low power consumption, and ease of use. The micro-controller on-board the Arduino unit allows the ADC conversion of the output signal which, eventually, is the signal that should be sent out to the main acquisition/recording system. Lastly, the wireless data transmission system is a custom made circular optocoupler, consisting of a LED ring in the rotating shaft and a photodiode placed in a stationary position close to the ring. This circular optocoupler transfers the digital data using the serial protocol.

To prove this concept, the full installation described above is implemented on a steel shaft, that incorporates the functions of the machine tool spindle, as well as the workpiece, as shown on Fig. 1. This system can be divided in eight sections: (1) a small diameter to be attached to the actual machine spindle; (2) an available section for the installation of a slip ring for power supply, if needed; (3) a smaller diameter where the strain gauges will be installed; (4) a section where all the data acquisition electronics will be placed; (5) a section that will feature the data transfer LED ring; (6) a thin flange that protects the electronics from metal chips; (7) a removable cylinder of metal to be machined and (8) a nut to keep the removable metal cylinder in place.

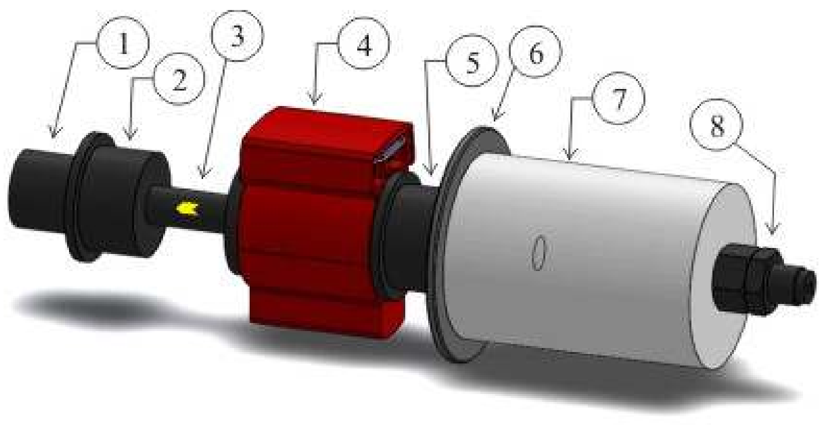

Figure 1. Instrumented shaft used in the test.

A finite element static analysis of the main component has been performed in order to assess the level of stress/strain in section (3), where the strain gauges were to be mounted. The diameter of this section is designed to withstand the cutting force loads while allowing a certain level of deformation for the proper reading of the load. Figure 2 shows a color plot of such analysis, with maximum stress of 29MPa uniformly distributed over the instrumented section.

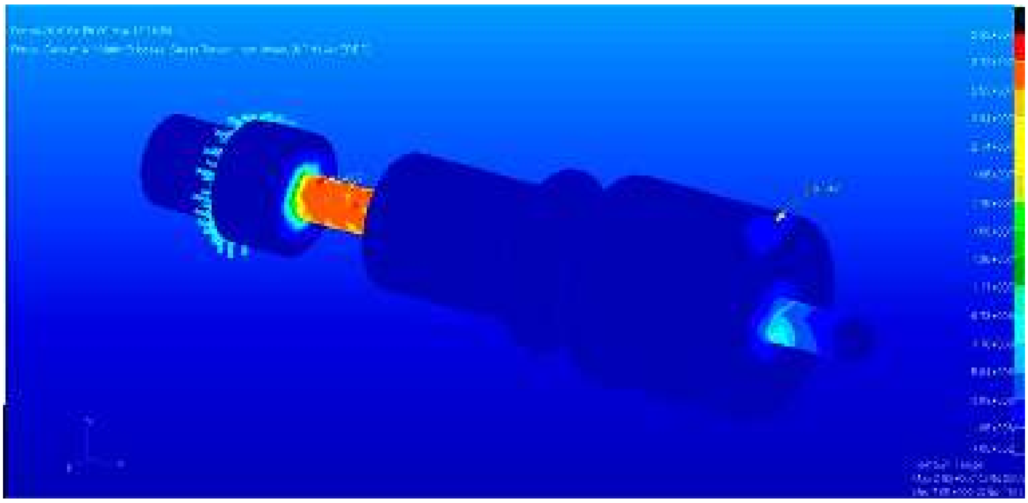

Figure 2. Finite element analysis of the instrumented shaft

The strain gauges used are HBM biaxial (fish spine) strain gauges with 350Ω. They are wired in a full bridge circuit, which is powered using a 3.3V source. The output of this bridge is connected to an instrumentation power amplifier chip, which boosts the output voltage, allowing the Arduino to read it on a better dynamic range with its 10-bit ADC. The circuit for the data acquisition system is shown on Fig. 3. The Arduino Uno is placed in a 3D printed case that is located in section 4 (Fig. 1). This section also features the instrumentation amplifier and a set of AAA-sized batteries to power the system at 12V.

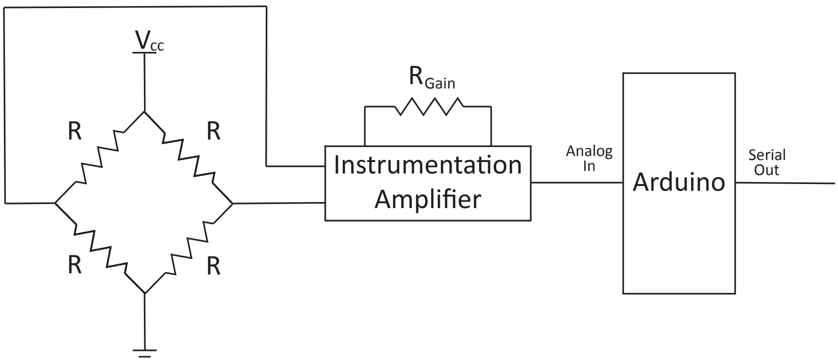

Figure 3. Schematics of the data acquisition circuit.

The wireless data transfer system, shown in Fig. 4, starts with the Arduino Uno placed on the axis. It reads the information from the strain gauges through an ADC and sends this information through its serial port. This serial signal is used to control the LED ring, making them all pulse simultaneously. Placed in front of the LED ring, in a stationary position, is the photodiode, responsible for interpreting the serial light signals emitted by the LED ring. The output of this photodiode is used as an input for a comparator, which is responsible for the normalization of the voltage, outputting only 0V or 5V. This output is read by a second Arduino, which then sends the data to a computer to be stored and analyzed. Both Arduino boards are working at a baud rate of 57600.

3. EXPERIMENTAL PROCEDURE

A prototype of the proposed wireless dynamic sensor has been built at the Dynamics Laboratory at EESC/USP, as seen in the Fig. 5. The leftmost side of the prototype is attached to the lathe spindle chuck while the rightmost side on the tailstock quill. The main part of the shaft, which holds the sensors, boards, etc. was oxidized to avoid wear. The bulk of stock material attached to it is the part supposed to be machined. That way it can be interchanged and allows for further evaluations of the system, under a wide range of cut conditions.

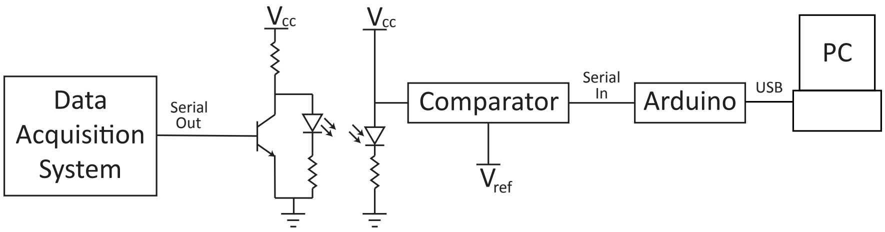

Figure 4. Schematics of the data transfer circuit.

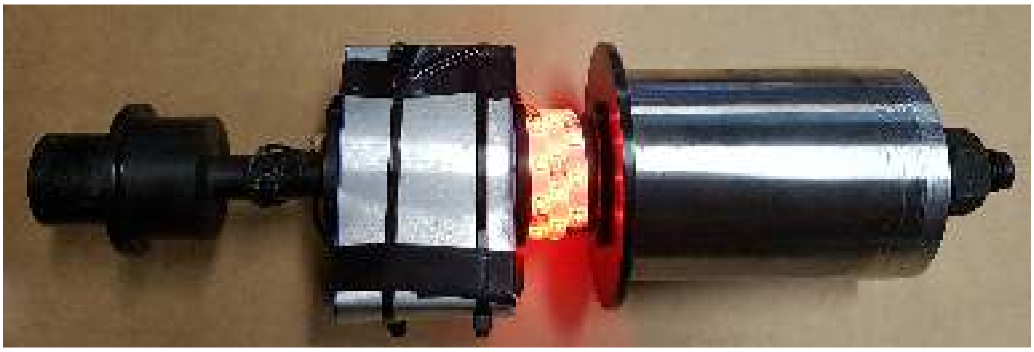

Figure 5. Final prototype used in the tests.

The experimental procedure presented here is part of a preliminary assessment of the system. It consists of three parts: (i) validation of data transmission system, (ii) static evaluation of strain measurements and (iii) data acquisition during machining operation. In the validation of the data transmission system, the device was rotated as if operating normally: fixed to the lathe chuck and revolving at normal operational speeds. It then transmitted a certain string of text repeatedly to the computer, allowing the user to easily spot mistakes in the data transfer.

During the static evaluation of strain measurements, the entire system was assembled and there was an attempt to measure the strain gauges while the axis was not rotating in order to check the data acquisition part of the system, sensitivity of the full measuring chain which includes the instrumentation amplifier and analog to digital converter. After that, a series of increasing torques was applied to the axis and the reading obtained from the measuring system was registered. After reaching the highest torque, the process was done in reverse to check for hysteresis.

In the final stage of testing, the entire axis was assembled and the metal cylinder was machined at 450 RPM and 0.3mm depth of cut, with the data being transferred to the computer and stored for post processing analysis.

4. RESULTS AND DISCUSSION

The validation of the data transmission system was conducted by sending a string of the same size as the messages to be used during the final operation of the project: three characters and a return character. This validation was done with the sensor shaft attached to a lathe, shown in Fig. 6. The tests were conducted at various different rotations, starting at 0RPM and going as high as 1200RPM. All of the tests showed that the system was capable of transmitting data without errors at a sampling rate of 785Hz.

Figure 6. Cutting force test on a lathe.

The next step shows the result for the static evaluation of strain measurements, wherein the entire system was assembled and affixed by the same end that was attached to the lathe chuck. An arm of 400mm was fixed to the opposite side of the test shaft, as close as possible to section 6 (workpiece) and loaded with calibrated weights. That way, the system was subject to equivalent levels of forces (and torque) as it would withstand during cutting operation. The force applied at the end of this arm was recorded by a dynamometer, together with the output coming from the measurement system, which can be seen in Fig. 7. The same sets of weights was applied to the free end of the shaft, without the torque arm (bending load) in order to assess cross-sensitivity effects. The measurement system did not respond to bending loads, only torsional loads, showing that the conceptual design achieved the expected performance.

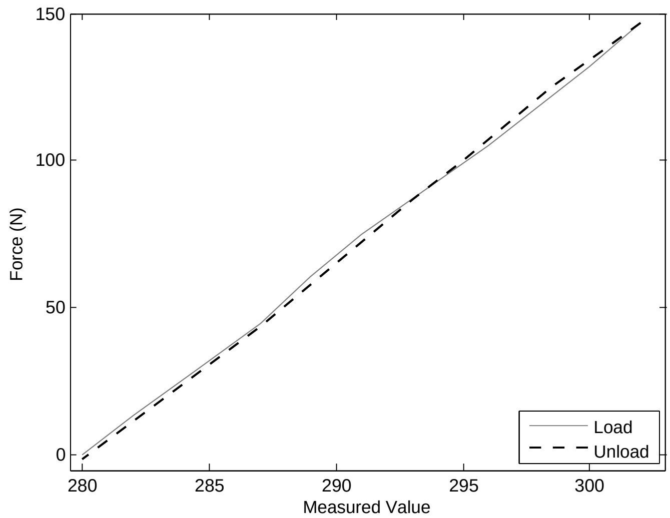

Figure 7. Measurement system calibration curve.

The results shown in Fig. 8 refer to machining at 450 RPM (2.15 m/s), 0.3 mm depth of cut with manual feedrate. The data acquisition rate for this process was 785 Hz, allowing for approximately 105 samples per revolution of the spindle. Aiming at observing the transient behaviour of the measuring system, the operator gave a total of five consecutive feed strokes within approximately 14s. A few different sections of these results can be highlighted: until 0.3s, the lathe is starting, from 0.3s until 2.5s it is rotating freely and from 2.5s until 16s the manual feeding occurs.

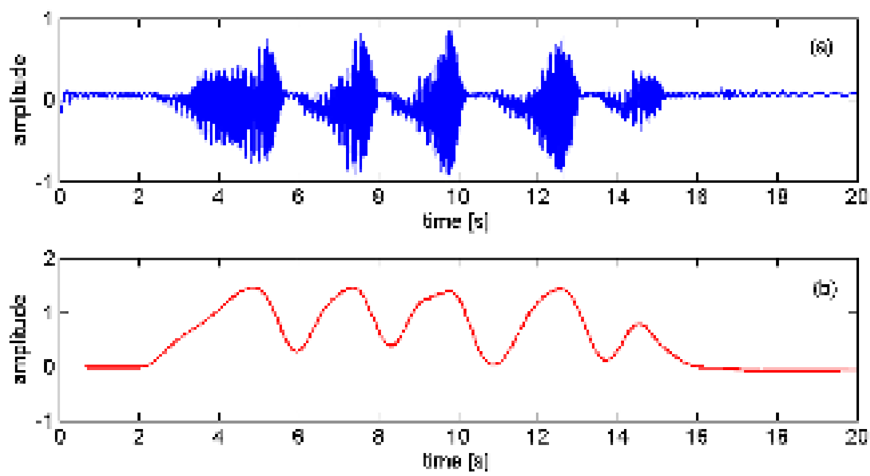

Figure 8. Torsional load measured by the proposed system cutting at 450 RPM: (a) raw time data and (b) torque envelope showing manual feed strokes.

While Fig. 8(a) shows the raw time data, corresponding to the torsional load on the spindle due to the cutting force, Fig. 8(b) shows the post processed data referring to the envelope of that load. These preliminary results show that this system is capable of measuring parameters of a machining operation from its rotating axis in real time, allowing for innovative approaches and sensor placements.

5. CONCLUSIONS

In view of instrumenting a machine tool towards Industry 4.0 goals, this paper introduces an optical telemetry system that allows sensors to be mounted directly on the machine's rotating parts, such as machine tool spindles.

The proposed telemetry scheme is thoroughly presented using a three-step procedure, which consists of evaluating the quality of the transmitted data (without measurements), the quality of the mechanical quantity measurement (without rotation) and, finally, the performance of the system under real operation when both, dynamic loads and rotation are present.

Preliminary results show that the system is sensitive to torsion, as intended, and can measure dynamic signals and static loads. Future work should be focused on improving frequency sampling as well as comparing the results obtained within this framework with standard cutting force dynamometers and/or static sensors mounted on the machine.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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