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Autonomous Vibration Spectrum-Based Spindle Health Monitoring System for Machine Tools

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Abstract*—Spindles form the heart of a machine tool system. Damage to the spindle directly reflects on the parts being produced by the machine. Monitoring the spindle's health is hence is necessary for early diagnosis of faults and defects such as to plan maintenance and repair. Though international standards guide monitoring solutions, there are no protocols for autonomous solutions. In response to the need for smart, autonomous monitoring solutions, this paper presents a novel vibration-spectrum based approach. The key components of our solution include automated spindle warm-up and thermal stabilization, high-speed data acquisition triggered at user defined spindle speeds, real-time spectral analysis, and robust fault detection and classification. Hardware components include an accelerometer, separate analog input and output modules, a digital input/output module, and a controller to run real-time FPGA communication. These components are all managed with a custom-built single-click software interface. We illustrate the monitoring protocols on an electro-spindle in a test bench and demonstrate its robustness. The level of automation in our solution far exceeds capabilities of any off-the-shelf spindle monitoring solutions.

***Keywords*—Spindle, Health monitoring, Vibration, Spectrum, Autonomous, Machine Tool.**

I. Introduction

Spindles form the heart of machine tools. They hold and transmit power to the rotating tool/workpiece. Any problem with the spindle due to damage to its rotating elements, or due to misalignments, or due to looseness directly reflect on parts being produced by the machine. Monitoring the spindle's health is hence necessary for early diagnosis of faults and defects such as to plan maintenance and repair, and to avoid damage to parts being machined [1].

The ISO standard's suggested indicator of spindle health is the root mean square (RMS) of the measured vibration accelerations levels from vibrations measured using a sensor mounted on the spindle housing [2], [3]. This data helps identify issues that could remain undetected during routine inspections. Capturing and analyzing this data allows for subtle anomalies in spindle behavior to be detected early, supporting the shift from reactive to predictive maintenance. The ISO standards suggest a threshold for these levels. And, if the vibration levels are above the suggested threshold, the spindle is likely damaged. Though the RMS is a statistically robust measure, it often masks faults and defects in the spindle system. The RMS levels are also prone to measurement uncertainties [4]. Hence, spectral methods are instead preferred [5].

As spindles with different defects and/or faults rotate, the defects and faults cause different periodic impulses. Hence, in the spectral method, defects and faults are diagnosed by a simple search for their corresponding frequencies from within the Fourier spectrum [6]. There exist off-the-shelf hand-held devices that can measure and classify faults based on spectral analysis [7][8]. However, since these hand-held devices require manual mounting of the sensor, measurements using them are also prone to uncertainties. Furthermore, since measurements can only be made when the machine is idle and when the technician is available, it is also difficult to make consistent periodic measurements with these devices. Since health monitoring requires measurement repeatability and requires the machine's state prior to measurements being consistent before every measurement, stricter protocols are necessary.

One such protocol was discussed in [9]. The researchers discussed the development of a dedicated automatic protocol in which the sensors were permanently mounted on the machine, and measurements were triggered every day at the same time after a warm-up routine was run on the machine. This was done by linking data acquisition hardware directly with the CNC system such that a call of a canned cycle to run the machine at different pre-set RPMs triggered signal acquisition for analysis. The analysis was conducted offline at later instants.

Since smart, autonomous machine tools should be able to self-diagnose their problems [10], there is a need to conduct the spindle defect and fault detection and classification in real-time and not offline as was done previously. As a step in that direction, and by taking inspiration from the excellent measurement protocol idea in [9], this paper presents an autonomous vibration-spectrum based health monitoring system for machine tools. In addition to establishing a robust measurement protocol, we include a clever and simple method to trigger signal acquisition and analysis in near real-time. Our proposed solution is customizable and cost-effective.

The key components of our solution include automated spindle warm-up and thermal stabilization, high-speed data acquisition triggered at user defined spindle speeds, real-time spectral analysis, and robust fault detection and classification. Hardware components include an accelerometer, separate analog input and output modules, a digital input/output module, and a controller to run real-time FPGA communication. These components are all managed with a custom-built single-click software interface. We illustrate the monitoring protocols on an electro-spindle in a test bench and demonstrate its robustness.

The remainder of the paper is structured as follows. Section II outlines the concept and discusses the key hardware components and their interfacing with software. Section III discusses the software setup. Section IV demonstrates working of the method. The paper is concluded in Section V.

II. PROPOSED CONCEPT AND KEY HARDWARE

We illustrate the concept on an electro-spindle with a maximum rpm of 24,000, and that has a rated torque of 0.8 kW. An overview of the concept is shown in Fig. 1.

The spindle is mounted in a housing on a table. These are not shown in Fig. 1. An IEPE piezoelectric accelerometer (make: Dytran; model: 3225F1) was wax mounted on the spindle housing. The output for this sensor is acquired using the National Instrument's (NI) 9234 digital I/O data acquisition system (DAQ). This DAQ is mounted in a slot in the chassis of the NI CompactRIO 9040 controller. This controller makes up the central hardware of the concept. It communicates with the spindle through two other hardware devices, namely the NI 9263 which is an analog output module for speed control, and the NI 9375 which is a digital module for turning on/off and controlling the rotation direction of the spindle. These two modules are also mounted in separate slots in the chassis of the NI 9040 controller. To communicate with the variable frequency drive (VFD) that drives the spindle, the NI 9375 parses signals through a buck convertor and through two relays. The relays control for on/off and direction, i.e., clockwise or counter-clockwise rotation of the spindle. Since the VFD needs a 0 V input, and since the NI 9375 supplies a 24 V output, the buck convertor performs a sourcing output and sinking input function.

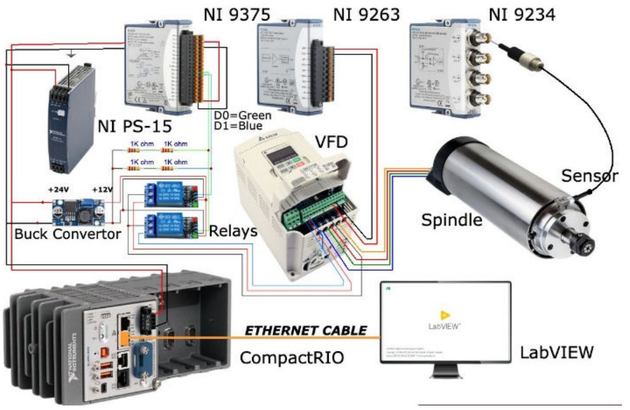

Fig. 1. Overview of the proposed autonomous spindle condition monitoring solution

The main 230 V AC power supply was connected to the VFD, the NI PS-15 power supply, and the computer. The NI PS-15, which converts AC to DC power, provided a 24 V DC output. This output was connected to the NI 9040, the buck converter input, and to the NI 9375, ensuring a common electrical ground was established across all components for stability.

Communication to/from the NI 9040 controller was through a LAN connection to a host computer running LabVIEW. The LabVIEW - NI 9040 has two communication functions. The first is the FPGA VI – that handles direct, real-time hardware communication. It acquires data from the sensors and manages two critical procedures. The first of which is a spindle warm-up cycle, and the second is a canned cycle that runs the spindle at user-defined speeds to trigger acquisition. The second communication protocol is the Real-Time (RT) VI – through which we perform higher-level data analysis. It executes a Fast Fourier Transform (FFT) on the sensor data to help classify defects and faults.

III. SOFTWARE SETUP

The real-time controller and the FPGA are programmed in LabVIEW to run thermal stabilization and triggering measurements and analysis. Running the spindle warm-up cycle, triggered data acquisition, and automated logging of FFT-analyzed peaks, are all managed via a single-click

LabVIEW interface, a screenshot of the frontend of which is shown in Fig. 2.

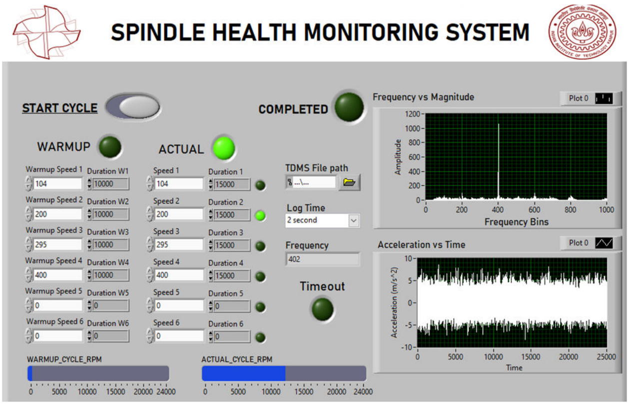

Fig. 2. Screenshot of the frontend of the software developed in NI LabVIEW.

To thermally stabilize the system, the user needs to enter speeds at which the spindle must be run at. The interface allows for up to six speeds to be entered. Speeds are to be entered in terms of the rotational frequency. Since thermal stabilization for machine tool spindles usually takes between 10 – 30 minutes [11], the duration to run the spindle at each speed is editable. The interface in Fig. 2 shows a default value of 10,000 milliseconds. This is for illustration only. Since thermal stabilization usually follows runs at low speeds followed by runs at higher speeds in a ramping-up manner, that is the order recommended for inputs. If running the spindle at six speeds is not desired, the user may set entries in all those cells as '0'. A wait bar shows the progress of the warm up cycle. And, the green-highlighted button shows if the warm-up cycle is active or not.

To acquire measurements for condition monitoring, the user needs to input the speeds at which vibrations must be recorded. These speeds are usually the speeds at which the spindle is to be run at during its use. We allow for up to six different entries. And, like for the case of the warm-up cycle, in this case too, measurement durations in milliseconds are to be entered by the user. Typically, measurements for health monitoring span 2 seconds for every speed, and that is what is recommended. And, like for the warm-up cycle, if fewer than six measurements are to be made, then the user may set all those cell entries as '0' in the interface. A wait-bar at the bottom shows the progress of the measurement.

The interface also has displays for what the measured accelerations look like along with a window showing the frequency spectrum of the measured accelerations. These are for display only. Data logging for storage and post-processing is prompted when the user starts the measurement cycle. That cycle can be started by a simple click on the 'start cycle' button. If there are missing entries as required for the warm-up and measurement cycles, then, in that case, the start cycle button will not get activated.

Once the cycle starts, and the warm-up completes, then at each speed set by the user, measurement is only triggered when the frequency spectra have peaks corresponding to the rotational frequency and/or one of its harmonics. This ensures that data is captured correctly for the speed of interest. We set the default rate of data acquisition to be 25.6 kHz, and also apply a low pass filter with a cut-off frequency of 10 kHz.

What sets our acquisition for condition monitoring apart is the high degree of automation and customization made available to the user through an easy-to-use interface.

IV. Demonstrating Condition Monitoring

To demonstrate the workings of our proposed autonomous concept, we measured the spindle shown in Fig. 1. We ran a three-spindle speed warm-up cycle for a total duration of 10 minutes, and measured vibrations at speeds of 200 Hz (12000 rpm), 300 Hz (15000 rpm), and 400 Hz (24000 rpm) for 2 seconds each. A record of the measured accelerations for these three speeds is shown in Fig. 3 along with their spectra.

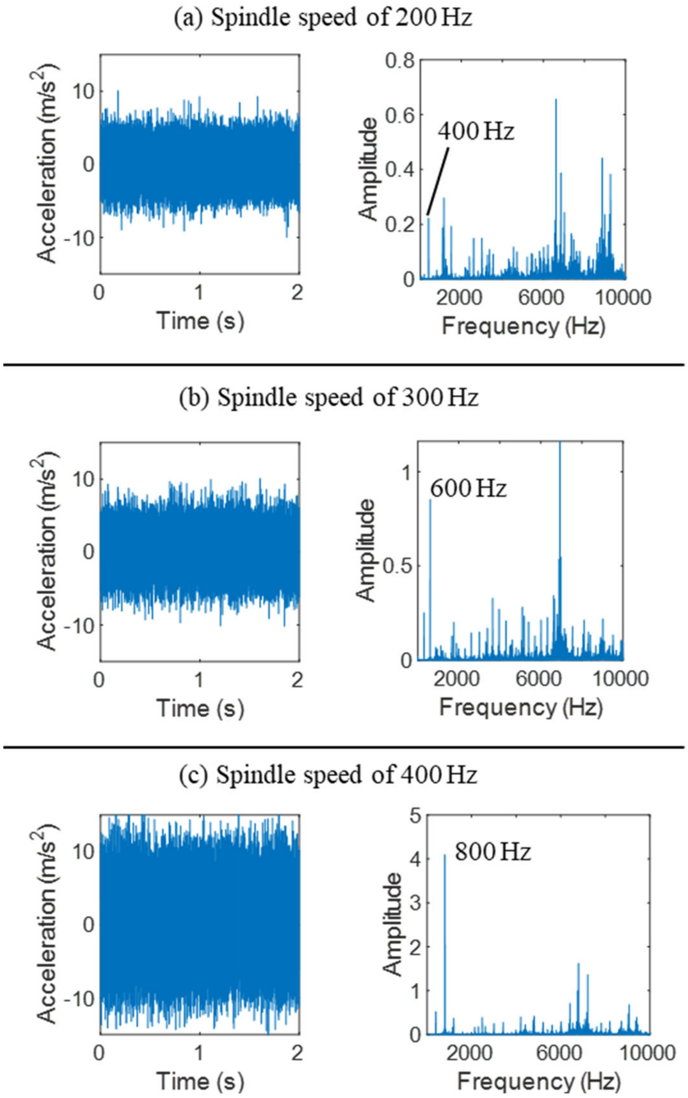

Fig. 3 Measured accelerations and their frequency spectrums: (a) spindle speed of 200 Hz, (b) spindle speed of 300 Hz, (c) spindle speed of 400 Hz.

As is evident from the measured accelerations, their levels increase with an increase in speed. This is not unusual [2,3]. The RMS level for the measurement at 200 Hz was evaluated to be 2.2 m/s^2 and it was 2.6 m/s^2 and 4.6 m/s^2 for the spindle speeds of 300 Hz and 400 Hz, respectively. The measured spectra in every case show multiple peaks in addition to the spindle rotational frequency and its first harmonic. The first harmonic being of stronger magnitude is also not unusual. It suggests there might be a slight runout in the holder mounted in the spindle. The other peaks with higher magnitudes could correspond to defects in the bearing races, or in the balls, or in the cages of the bearings. Classifying which peak corresponds to which defect is rather straightforward, and can be done following procedures described in [12] and in [6]. It should be noted that the spindle system is relatively new, with a total run time of less than ten hours. Hence, the defect signatures visible in the spectra are likely not due to damage in the spindle system. Even relatively new spindles, with new bearings exhibit peaks corresponding to defects in the spectra [9]. Those defects are usually due to manufacturing and assembly process related issues.

The application we've developed and presented has been shown to be capable of monitoring the spindle's health using vibrations and vibration-spectrums. The RMS levels can be easily benchmarked with thresholds suggested by the ISO standards and cases can be flagged as healthy or damaged. Furthermore, the accompanying spectral information can help detect and track the evolution of faults and defects in the spindle system to plan timely maintenance and repair.

Though the concept was demonstrated on a single spindle, the application is easily generalizable, and can run stand-alone with any CNC machine. Integration with the CNC controller is also possible. For now, all the operator/technician has to do is to run a pre-programmed canned CAM cycle on the CNC machine that will run a warm-up and measurement cycle, and click on the 'start cycle' button on our application to trigger monitoring.

V. CONCLUSIONS AND OUTLOOK

This paper presented a new, smart, autonomous spindle health monitoring solution that tracks measured vibration levels and combs through the spectra to find and classify peaks corresponding to faults and defects in the spindle system. A generalized single-click software application communicates in real-time with the hardware for thermal stabilization, measurement, acquisition, and speed-control. The monitoring protocols were illustrated on an electro-spindle in a test bench. The level of automation and customization that is possible in our solution far exceeds capabilities of any off-the-shelf spindle monitoring solutions.

What we've built and demonstrated is a monitoring protocol, and not a classification one. Building a classification protocol is different than building a monitoring protocol. Classification requires details about the size of the spindle and its bearings, and since that information varies from machine tool/spindle maker to maker, future work could explore combining a monitoring protocol with a database that contains details about the spindle and its bearings to also enable efficient classification. Future work could also focus on integration with the CNC controller, and an automatic report generation process with trend analysis to track the evolution of faults and defects to help build a robust remaining useful life predictor. Furthermore, since the hardware used in this demonstrator is expensive, future work could also explore the development of the solution on open-source and inexpensive hardware and software.

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