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Perils of vibration RMS-based spindle health monitoring

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Abstract: Spindles vibrate due to imbalances, misalignments, looseness, cutting force-based excitations, and bearing defects. Since vibrations deteriorate part quality and the life of the spindle and the machine, monitoring can help in prognostics for condition-based spindle maintenance and in diagnostics for root cause analysis of failures. The ISO 17243 standards recommend monitoring RMS levels of the spindle's vibration. RMS levels are, however, as shown in this paper, a bad proxy for the spindle's health. With measurements on a representative machine tool spindle, we show that RMS levels are corrupted by uncertainties related to sensor mounting, spindle condition at the time of measurement, and other sources of excitation. Variations in RMS levels are found to be up to 68% - much larger than the ±10% uncertainty recommended by the standard. Root cause identification of the nature of the fault or defect is also not possible with RMS levels. Since RMS-based spindle health condition monitoring is perilous, we instead propose that the standards be revised and be based on vibration spectrum-based analysis.

Keywords: Condition monitoring, Vibration, RMS, Spindle, Spectral, ISO 17243

1. Introduction

Spindles vibrate. These vibrations result from imbalances, misalignments, looseness, cutting forces, and bearing defect-induced vibrations [1,2]. Since all such vibrations are bad and contribute to deterioration in part quality and life of the spindle and the machine, and since spindles form the heart of machine tools, monitoring their condition using vibrations can help in prognostics for condition-based spindle maintenance and in diagnostics for root cause analysis of failures. Such health monitoring is also necessary to realize 'smart factories', i.e., factories in which machines can autonomously monitor and diagnose problems with themselves.

The International Organization for Standardization (ISO) has two standards related to condition monitoring of machine tool spindles – the ISO 17243 – 1 [3] and the ISO 17243 – 2 [4]. The standards recommend measuring the spindle's no load vibrations using accelerometers mounted on the spindle housing. Standards recommend measuring in two radial directions near the front and rear bearings. And, to assess the health of the spindle, the standards recommend that if/when vibration velocity and acceleration RMS levels are beyond prescribed thresholds, then the spindle could be damaged.

Though the ISO standards are established by having monitored a significant number of machines made by several large multinational machine tool manufacturers over a period of 15 years, and even though standards such as these have been used to monitor the health of machine tool spindles [5], the standards' reliance on vibration RMS levels as a proxy for the spindle's health is perilous.

RMS levels are susceptible to measurement errors and uncertainties due to environmental factors unaccounted for in the standards. The first and major source of uncertainty is the method of mounting the accelerometer. Since most accelerometers work on the principle of base excitation [6], they must be screw mounted rigidly on the spindle housing. This is only possible if the accelerometer is permanently mounted on the machine. However, since most measurements are made with transducers that are magnet mounted so that they can be easily moved from machine to another, and if the mounting surface is not flat or has dust or chips or oil on it, measurements are corrupted. The other main source of uncertainty not accounted for in the standard is how extraneous factors influence measurements. These factors include the condition of the spindle just before measurement such as, was the spindle idle or not, at what speed it rotated at just before the measurement and for how long, and how long has the spindle has been in operation, i.e., number of running hours. The other extraneous factors include the time of the day at which measurements are made - drastic changes in ambient temperatures could influence spindle thermal growth, and in turn their vibration signatures. Yet other extraneous sources include potential excitations from neighboring machines corrupting the vibration levels of the machine being measured.

To demonstrate the perils of vibration RMS-based spindle health monitoring, this paper presents the results of systematic experimentation on a representative 3-axis CNC vertical milling machine. Experiments are undertaken to demonstrate uncertainties in repeatability of the measurements by magnet mounting accelerometer on the spindle housing, measuring, removing the sensor, mounting it again and measuring again. Further experiments are undertaken by changing the condition of the spindle before measurements. In one case the spindle is warmed up for a few minutes, and in another case the spindle is kept running for an hour before measurements. Measurements are also undertaken at different speeds. This experimental plan and its results are discussed in Sections 2 and 3 of the paper.

Since the main argument of this paper is that vibration RMS-based monitoring is a bad proxy for the health of the spindle, in Section 4 we discuss how vibration spectrum-based analysis should instead become the default mode for spindle health monitoring. Though vibration spectra are computed from the same data that the RMS is computed from, which is the measured accelerations, the spectra is richer. In general, for measurements of the rotating spindle during a no load non-cutting operation, the spectra for healthy spindles should only contain a frequency peak corresponding to the rotational frequency. If the spectra contain other peaks, it suggests something is out-of-the ordinary [7,8]. Since frequencies related to spindle looseness, misalignments, and bearing related defects are well-defined [1], it is easy enough to classify what, if anything, is failing, or has failed. We motivate how such spectral analysis can augment spindle health monitoring standards. The paper is finally concluded in Section 5.

2. Experimental setup and plan to monitor spindle vibrations

We measured spindle vibration behavior on an AMSL make ACER series 3-axis CNC milling machine. We magnet mounted a single axis accelerometer (make: Wilcoxon Research; model number: 785A;

sensitivity: 100 mV/g) on the spindle housing near the front bearing location. Fig. 1(a) shows this setup for the representative X direction of measurement. We also measured Y directional accelerations separately by moving the same sensor to the direction of interest. A balanced tool and tool holder were mounted in the spindle and the spindle was run at differed speeds to measure the resulting vibrations. No load vibrations were measured, i.e., when there was no cutting action. The spindle was kept in the middle position of all its X-Y-Z strokes for all measurements. We acquired data at 25.6 kHz. We used NI's 9234 data acquisition hardware together with NI's 9171 chassis. Accelerations were acquired using MATLAB's signal processing toolbox. Signals were not pre- and/or post-processed. All measurements were made over a period of at least 5 seconds. RMS of measured accelerations were directly estimated in MATLAB. It should be noted that the spindle on the machine was healthy, with no reported faults and or defects.

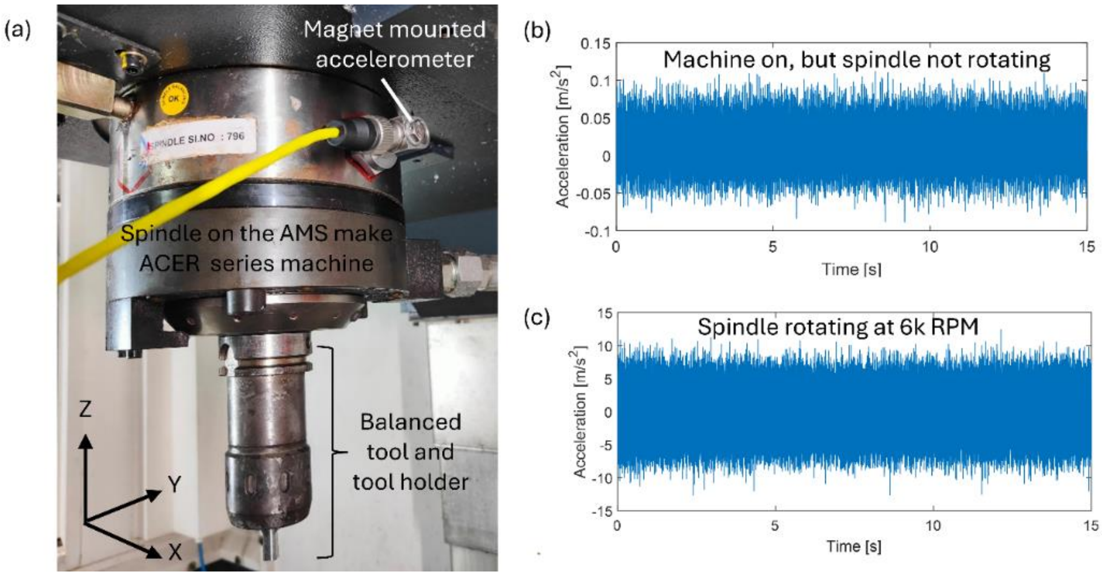

Fig. 1. (a) Experimental setup to measure spindle vibrations, (b) representative measured accelerations for when the machine was on and the spindle was not rotating, and (c) representative measured accelerations for the spindle rotating at 6000 RPM.

The experimental plan was designed to check for uncertainties in measurements. The plan was as follows: at first, to establish the baseline noise in the vibration response, measurements were made with the machine being off, and with the machine on, but when the spindle was not rotating. Measurements were then made at four distinct spindle speeds: 2k RPM, 6k RPM, 10k RPM, and 15k RPM. At each speed, we first measured the response a minute after the spindle was run at that speed. We repeated this measurement by measuring in quick succession (i.e. restarting the spindle). We then removed the sensor and mounted it again at the same place and then repeated the measurement. This was followed by running the spindle for 60 minutes and repeating the measurement. Since there were four measurements at every speed, and since we measured at four different speeds and in two directions, the total number of measurements became 32. Two representative acceleration measurements corresponding to a case when the machine was on, but the spindle was not rotating, and to a case when the spindle was rotating at 6000 RPM are shown in Fig. 1(b) and Fig. 1(c).

3. Variation in measured vibration RMS levels

RMS levels for all measurements are listed in Tables 1 and 2 for the X and Y directions, respectively. The baseline vibration noise response when the machine was off, and when the machine was on, but the spindle was not rotating was 0.0174 m/s^2 and 0.0245 m/s^2, respectively. Since these levels are two orders of magnitude less than the measurements during rotation – see Tables 1 and 2, all measurements are considered to be relatively noise-free.

Table 1. Measured accelerations in the X-direction. Unit of acceleration is m/s^2

RPM	At start	In quick succession	After re-mounting the sensor	After 60 min.
2000	1.30	1.38	1.00	0.82
6000	2.33	2.37	2.47	2.39
10000	2.44	2.52	3.21	2.95
15000	4.19	4.13	3.62	3.43

Table 2. Measured accelerations in the Y-direction. Unit of acceleration is m/s^2

RPM	At start	In quick succession	After re-mounting the sensor	After 60 min.
2000	1.38	1.57	1.64	0.98
6000	4.94	5.05	3.96	2.72
10000	3.35	3.46	3.21	3.55
15000	5.10	4.83	3.91	3.28

As in evident from Tables 1 and 2, all measurements made in quick succession of each other appear to be repeatable within $\pm$10%. However, the variations in measured accelerations after removing and re-mounting the sensor increase up to 30% - 38% in some cases - see X-directional response at 2k RPM and Y-directional responses at 6k RPM and at 15k RPM. Variations further increase to 55% - 68% after running the spindle for 60 minutes - see X-directional response at 2k RPM and Y-directional responses at 15k RPM. Since the ISO standards recommend that any uncertainties in measured RMS values be within $\pm$10% of the nominal value [3,4], and since our systematic measurements show that uncertainties due to sensor mounting and the state of the spindle (warm or cold start) at the time measurements can be up to 68%, it is clear that the vibration RMS level is not a very reliable indicator of the spindle's health. For instance, with these levels of uncertainties, it would be impossible to distinguish between a high RMS level signaling a fault or defect in the spindle system or the high RMS level simply being an artefact of the uncertainty of the measurement. It should also be noted that though not accounted for herein, other environmental factors such as thermal growth-related change in vibrations and/or excitations from neighboring machines will further add to uncertainties in the RMS estimated.

Since we have conclusively demonstrated the perils of vibration RMS-based spindle health monitoring, we now turn our attention to suggesting ways to make more robust decisions about the health of the spindle based on measured vibration data – as is discussed next in Section 4.

4. Making the case for vibration spectrum-based health monitoring

As demonstrated already, RMS levels are an inadequate indicator of the spindle's health. Moreover, RMS levels mask defects, i.e., even though the spindle system may be damaged, RMS levels may appear within specifications. The converse may happen too especially when the uncertainties in the measurements are as high as demonstrated herein, i.e., it is possible that RMS levels are beyond specifications, but the spindle is healthy. And, even in situations when RMS levels are consistently above specification, it is difficult to identify the root cause of the increase in vibrations, since RMS levels mask causes too.

Since existing vibration RMS-based methods are inadequate, we suggest that spectral-based methods be used instead to monitor the spindle's health. Spectral analysis plots the Fourier spectra of the measured time series accelerations, and classifying faults, defects using spectra is relatively straightforward. If the spindle is healthy, then its spectrum should only contain a peak corresponding to the rotational speed. And, if the spectrum has any peaks that are not at the fundamental rotation speed, then a simple check can confirm if those peaks correspond to faults such as looseness, and/or misalignments, or defects in the bearing. For example, misalignments are characterized by harmonics of the spindle rotational frequency being present in the spectra and having magnitudes greater than the peak corresponding to the fundamental rotational speed. Likewise, looseness is characterized by the presence of higher harmonics of the spindle rotational frequency accompanied by fractional sub- and super-harmonics of the spindle rotational frequency. Bearing defects too are easily classified as being due to the outer race, or the inner race, or the ball, or the cage, and all of these are a function of the rotational speed, the number and the size of balls, the geometry of the raceways, and the contact angle for the case of angular contact ball bearings.

It should also be noted here that condition monitoring that is based on spectral analysis will be more robust than the RMS-based methods prescribed in the standards. Even though uncertainties that corrupt the RMS levels will also influence the spectral analysis method by potentially changing the strengths of different peaks in the spectra, since classification of faults and defects is only based on detection of corresponding peaks in the frequency spectra and not the magnitude of those peaks, even if the measured acceleration data has uncertainties those uncertainties are not expected to corrupt diagnostics.

Though spectral methods can help diagnostics, the methods are not suitable for prognostics. At least not yet. The main reason for this is the lack of systematic trend analysis that can help establish amplitude thresholds to warn about the severity of the faults and defects, when faults and defects are detected. This is much like the RMS thresholds for velocities and accelerations provided by the ISO standards. Those RMS standards have been developed based on years of monitoring many different spindles. However, since no such thresholds exist for spectral analysis, these thresholds will need to be established. This will require monitoring the evolution of spindle faults and defects until failure. And, for any such threshold to be useful, it would require monitoring potentially thousands of spindles until failure. Such a task is only feasible when set up by a standards committee at the international level. We hope that arguments made in this paper against the use of RMS levels and in support of spectral analysis can help inform the development of much needed spectral analysis-based spindle health monitoring guidelines.

5. Conclusion and outlook

This paper, through systematic experimental characterization of the vibration behaviour of a representative machine tool spindle, demonstrated the inadequacy of using vibration RMS levels to monitor the health of the spindle. We showed that the measurement uncertainty in the RMS levels is up to 68%. Major uncertainties were due to sensor mounting issues and the state of the spindle at the time of measurements. Since uncertainties were significantly more than the $\pm 10\%$ uncertainty recommended by the ISO standards on condition monitoring of spindles based on RMS levels, we conclude monitoring the health of spindles based on vibration RMS levels is perilous. We also motivated the need to move to a spectral-based spindle health monitoring method. Since there are issues with vibration RMS-based spindle health monitoring, and since spectral analysis of the vibration data is richer and can be more easily used to classify faults and defects, we motivated and proposed that spindle health monitoring standards must be revised and be based on vibration spectrum-based analysis.

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