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Evaluating Spindle Degradation and Machining Quality Using an Exchangeable Spindle Unit and Vibration-Based Monitoring

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Abstract

Spindle units are one of the most important sub-systems in the machine tools and play a crucial role in the reliability of the system and quality of the machined parts. Spindle units using rolling element bearings are the most widely used type, due to their low friction and good load capacity. Unfortunately, within the manufacturing environment, they are subject to impacts, wear and rough working conditions that affect the lifetime of their components, especially the bearings. To systematically analyze spindle degradation, an exchangeable spindle unit (ESU) was implemented as a flexible platform for introducing errors such as bearing errors, unbalance, and mechanical looseness. These error modes were evaluated using vibration measurements, while surface roughness parameters were evaluated to identify patterns linking spindle condition to machining quality. Results demonstrate the potential of vibration-based monitoring for machining stability assessment and predictive maintenance.

Spindle, Error, Diagnostics, Machining

1. Introduction

Machine tools are the cornerstone of modern manufacturing, and spindle units are among the most critical components of these systems. A spindle unit provides the rotating force that drives the cutting tools, making it essential for ensuring both productivity and quality of machined parts. As such, its reliability has a direct impact on the performance and efficiency of manufacturing operations. Spindles using rolling element bearings are particularly popular for their low friction and good load capacity. However, these spindles are subjected to challenging conditions in the production environment, such as impacts, contamination, and vibrations, which can lead to accelerated wear and degraded performance over time. Given this context, the motivation behind this study is to improve understanding of spindle units' error modes, particularly in how they influence the machined parts' quality.

The aim of this study is to investigate the impact of spindle condition changes on machining quality by introducing controlled errors into a spindle unit designed to change (ESU). Specifically, the study aims to evaluate the effect of bearing errors, rotor unbalance, and mechanical looseness in machining using vibration measurements. The outcomes can be used to develop improved diagnostic tools for spindle maintenance and improve condition-based maintenance strategies.

2. State of the art

The use of sensors and metrology systems is becoming more common in advanced manufacturing [1]. The integration of real-time monitoring tools enables improved diagnostics and maintenance strategies. Recent developments link vibration diagnostics with surface roughness measurements, providing deeper insights into machine health and product quality. AI and statistical models have further enhanced predictive capabilities, enabling real-time assessments of machining conditions [2, 3, 4].

Rotor unbalance is a major contributor to spindle vibration, primarily caused by uneven mass distribution in rotating components. Experimentally induced unbalance increases synchronous vibration levels, leading to tool path deviations and periodic surface waviness [5,6]. Similarly, bearing wear significantly impacts spindle performance, increasing vibration levels and compromising precision [7]. To study these effects, researchers commonly introduce pre-damaged or artificially modified bearings [8, 9, 10]. However, such experiments on actual machine tool spindles are costly and require extensive disassembly and reassembly.

To address this challenge, researchers develop test platforms to evaluate machining performance under controlled bearing defect conditions [9]. However, existing setups often have limitations regarding the number of tests that can be conducted and the range of errors that can be analyzed.

Despite these advancements, a significant gap remains in understanding how different spindle faults interact and their combined effects on machined surface roughness. To bridge this gap, this study introduces an exchangeable spindle unit (ESU) that allows for the controlled introduction of errors, both individually and in combination, to systematically evaluate their impact on machining performance and surface quality. This approach aims to enhance predictive maintenance strategies and provide a deeper understanding of how spindle degradation affects manufacturing outcomes.

3. Methodology

Errors in spindle units can significantly impact the performance and precision of machine tools (e.g., synchronous and asynchronous motion errors), resulting in poor surface quality and potential downtime. In this study, a specially designed ESU (Figure 1) is used to introduce controlled errors, providing a flexible platform for evaluating various fault conditions in a real machining process. The ESU consists of a bearing cartridge equipped with high-precision spindle bearings, assembled into the ESU housing that is attached to the main machine tool spindle nose. The bearing cartridge is connected to an HSK tool holder in the main spindle via an elastic coupling. This configuration facilitates the transfer of rotational power from the machine tool spindle to the cutting tool. The elastic coupling isolates vibrations and error modes from the machine tool while allowing for thermal expansion. The design of the ESU enables the attachment of the unit into an existing spindle to make use of machine tool characteristics. Error modes including incremental bearing wear, rotor unbalance, and mechanical loosening are introduced individually and in combination. The effects of introduced errors on spindle unit operation are analysed using vibration measurements, while machining quality is evaluated by analysing surface roughness of machined slots.

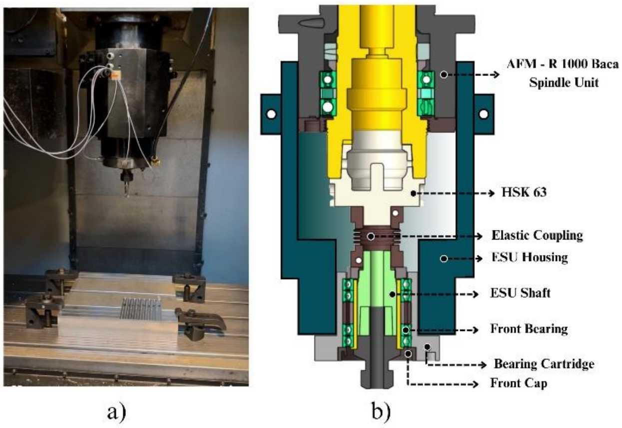

Figure 1. a) Machining setup. On top the exchangeable spindle unit (ESU) mounted and clamped to the machine tool spindle nose, the accelerometers connected and the blank clamped to the machine table. b) ESU components in CAD cross section view.

Defects in spindle units can significantly affect the performance and precision of machine tools, leading to poor machining results and potential downtime. Common defects include bearing wear, unbalance, and mechanical looseness. In order to investigate how these errors affect the surface roughness of machined parts, a Design of Experiments (DoE) was developed following a full factorial design, considering bearing wear, spindle speed, unbalance mass, mechanical looseness and two levels of cutting depths as independent variables. In the front bearing wear was divided into three levels: None (I), Medium (II), and Severe (III). Spindle speed was set at 3000 1/min for odd-numbered slots and 4000 1/min for even-numbered slots. Unbalance was introduced at two levels: Medium and High. Mechanical looseness was considered at two levels: Non-loose and Loose. Finally, cutting in three levels: no-cutting, 1mm and 2mm depth of cut. These parameters were chosen to replicate actual conditions of semi-finishing cuts.

A total of 36 experimental runs (slots) were conducted by systematically varying these parameters. At each of the machined slots the tree levels of cutting were tested: no cutting, 1mm and 2mm depth of cut as described in table 1. This structured DoE allowed for a systematic evaluation of the individual and combined effects of spindle speed, unbalance, looseness, bearing wear and machining condition on vibration behavior, and surface roughness.

Table 1 Full factorial design with the 36 slots machined each one with a different condition

Slot	Bearing wear level	Spindle speed (1/min)	Unbalance mass	Mechanical looseness
1, 13, 25	I, II, III	3000	Non	Non
2, 14, 26	I, II, III	4000	Non	Non
3, 15, 27	I, II, III	3000	Medium	Non
4, 16, 28	I, II, III	4000	Medium	Non
5, 17, 29	I, II, III	3000	High	Non
6, 18, 30	I, II, III	4000	High	Non
7, 19, 31	I, II, III	3000	Non	Loose
8, 20, 32	I, II, III	4000	Non	Loose
9, 21, 33	I, II, III	3000	Medium	Loose
10, 22, 34	I, II, III	4000	Medium	Loose
11, 23, 35	I, II, III	3000	High	Loose
12, 24, 36	I, II, III	4000	High	Loose

To evaluate the results, time-series acceleration data was pre-processed to remove noise and transformed into the frequency domain using Power Spectral Density (PSD). This transformation allowed for the identification of bearing damage characteristic frequencies, including Fundamental Train Frequency (FTF), Ball Spin Frequency (BSF), Ball Pass Frequency Outer race (BPFO), and Ball Pass Frequency Inner race (BPFI) [9]. The PSD analysis provided insights into how these characteristic frequencies evolved under different cutting conditions and demonstrated the influence of spindle degradation on the spectral content of vibration signals. Key time-domain statistical features such as Root Mean Square (RMS), Peak-to-Peak, Kurtosis, Mean, Standard Deviation, and Skewness were extracted from the vibration data to asses sensitivity to spindle defects. These features were analyzed across different wear conditions to identify trends linked to machining instability.

To further explore the relationships between vibration behavior and surface roughness, machined surface roughness measurements, for the 2 mm depth of cut, were analyzed alongside the extracted vibration features. Principal Component Analysis (PCA) was applied to reduce dimensionality and highlight the most dominant features influencing both vibration response and machining outcomes. The PCA results were used to cluster machining conditions based on wear progression, identifying trends in how spindle condition affects surface roughness. This integrated approach provided a systematic evaluation of wear progression and its impact on both machine dynamics and machining performance.

3.1. Method for error injection

In order to systematically introduce wear on the ball bearing balls, the process begins by securing the ball in a fixed position using an aluminium ball fixture. A 2 kg weight is then applied to exert pressure on the ball against abrasive media (P100), thereby accelerating the abrasive wear process. Subsequently, the sandpaper is moved over 500 mm to ensure consistent and measurable wear on the ball (Figure 2). Level I, corresponds to no wear or healthy bearing, level II consisted of scratches in the surface. Finally, severe wear level III consisted of a flattened surface area.

To simulate the unbalance error, two levels of unbalance were implemented by attaching screws of 0.38 g and 0.73 g to the front end of the ESU shaft (Figure 1) at a distance of 20 mm from the axis of rotation. This approach ensured controlled and repeatable variations in the system's dynamic response. Finally, to introduce mechanical looseness into the system, the front cap of the ESU (Figure 1), which keeps the bearing package in place, is loosened with a wrench by unscrewing it 90 degrees. Prior to loosening, alignment marks were made on both the cup and the housing to ensure consistent repositioning during subsequent adjustments.

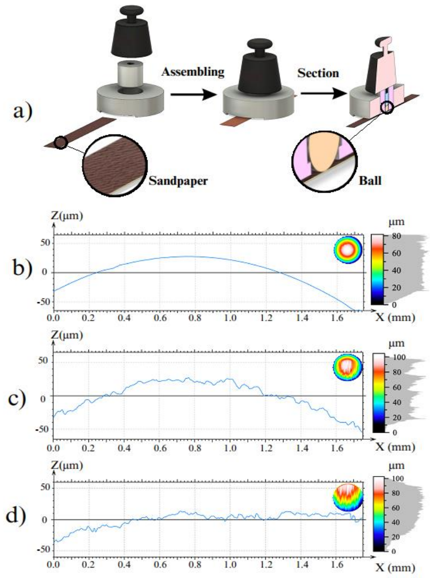

Figure 2. The ball error injection test setup CAD model (a) and the scanned result of introduced ball abrasive wear: No damage on level I (b), medium on level II (c) and severe on level III (d).

3.2. Experimental investigation

The experimental tests were performed on a 3-axis machining center (Baca R1000). The ESU was mounted to the spindle nose and secured in the spindle tool clamping system to ensure a stable and repeatable setup during machining operations (Figure 1). A cylindrical high-speed steel (HSS) milling tool with a diameter of 12 mm and three cutting edges was used for the cutting experiments to maintain lower spindle speeds and feeds, and by that, maintain a tighter control over the machining process. Since two spindle speeds were tested the feed per tooth was kept constant at 0.09 mm/tooth adjusting the feed rate accordingly.

The workpiece consisted of a pre-machined aluminum 6082 block featuring a 1 mm step with a step length of 60 mm. This design ensured at least 3 seconds of stable cutting time for each of the conditions defined in the DoE. The cutting process selected for this investigation was slot milling as it provides a simple and repeatable experimental setup for controlled analysis. In this operation, the tool begins cutting at a depth of 1 mm, transitions through the step, and completes the cut at a depth of 2 mm. A total of 36 slots were machined.

A Zygo NewView 7300 white light interferometer was used to measure the wear on the bearing balls. This instrument provides high-resolution measurements, enabling detailed characterization of wear morphology and size.

Three uniaxial accelerometers were used to acquire vibration data during the experiments. The sensors used were HBK 4534-B-002 and were directly mounted on the spindle, above the front bearing (Figure 1). The sampling rate was set at 5000 Hz and the data acquisition system used for recording the signals was a National Instruments cDAQ-9185, which ensured synchronized and high-resolution data collection across all sensors.

The surface roughness of the machined slots was measured using a profilometer Mitutoyo SurfTest mounted on a support. Measurements were performed in a length of 4 mm at the center of the slots with a 2 mm depth of cut to assess the effects of cutting conditions and system degradation on surface quality. This measurements aimed to show the trend of surface texture changes in relation to the severity of the introduced errors.

4. Results and discussions

The vibration signals from the different slots were analyzed in the frequency domain, up to a frequency slightly above the Ball Pass Frequency Inner race (BPFI). The resulting Power Spectral Density (PSD) plot for Slot 36 (Figure 3) highlights the impact of machining on the spectral content. Specifically, a reduction in the amplitude of frequency peaks is observed in the Y-axis (cutting direction), while amplitudes increase in X-axis. A notable example is at the third harmonic frequency (3x F), at which the Y-axis exhibits -7 dB/Hz at 2 mm cutting depth, while the X-axis shows a significantly lower amplitude of -20 dB/Hz.

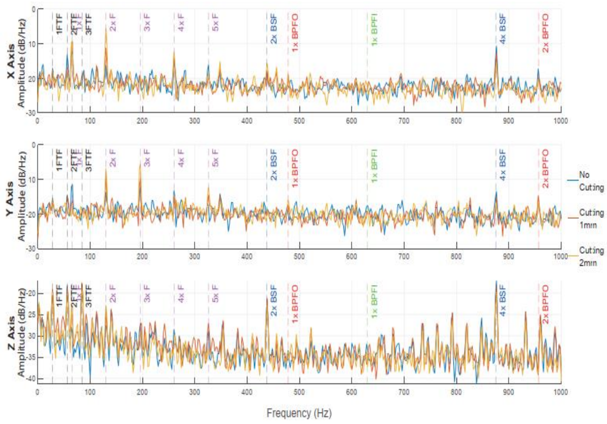

Figure 3. PSD plot of last slot number 36 with X, Y and Z measurements.

Additionally, bearing wear is visible in the frequency spectrum. A clear defect is observed at the second harmonic of 2× BSF, with a pronounced spike in all three directions, though the lowest amplitude occurs in the Y direction. Another notable observation is that second harmonics exceed first harmonics, which may be influenced by the coupling in the system. This effect is particularly noticeable in the third harmonic in the Y direction (cutting direction). Furthermore, the Z direction exhibits spikes at FTF harmonics, suggesting a possible cage defect. Similarly, BPFO shows a pronounced second harmonic, which may be attributed to the defect on the bearing ball itself. The Z axis also has more peaks overall, likely due to mechanical looseness, allowing increased movement in that direction.

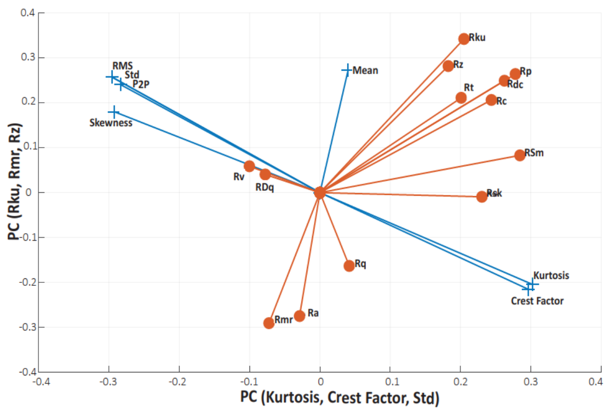

Figure 4. PCA biplot with acceleration features and roughness parameters. Vectors closed one another suggest positive correlation and opposed vectors suggest inverse correlation.

A Principal Component Analysis (PCA) was performed to explore correlations between higher-order statistical features from the accelerometers and surface roughness parameters.

The resulting biplot (Figure 4) reveals the most dominant contributors to the principal components (PCs).

For the acceleration data, the primary contributors are Kurtosis, Crest Factor and Standard Deviation, while for the roughness parameters, the most influential features are Rku, Rmr and Rz. Interestingly, Crest Factor and Standard Deviation / RMS are positioned in opposite directions, suggesting an inverse correlation. A similar relationship is observed between Mean roughness (Ra) and Mean acceleration. It is also noteworthy that Rsk lies along the horizontal axis, suggesting that this parameter is greatly influenced with vibration features.

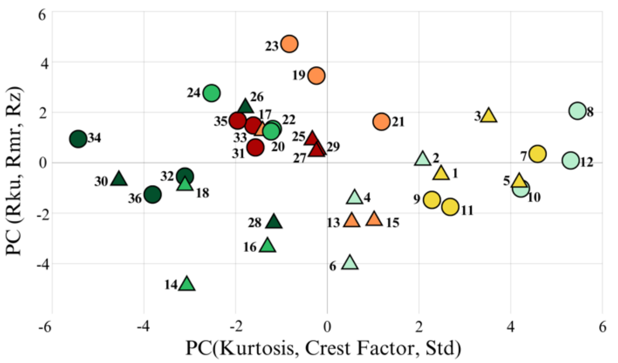

Figure 5. PCA scatter plot. Even slots are represented in shades of orange and odd slots in green. Slots are clustered according to the condition, unbalance in circles and looseness in triangles. The bearing wear level is represented by three distinct colors: the lightest color indicates no damage (level I), the middle shade represents level II wear, and the darkest color signifies level III damage

Figure 5 presents the PCA projection of roughness and vibration features, showing how the machined slots cluster in different regions of the plot. Before applying the first level of wear to the bearing ball, the clusters are concentrated toward the right side of the PCA space, indicating low variability in both surface roughness and vibration behavior.

As bearing wear increases, the clusters exhibit higher dispersion, implying increased variability in roughness parameters within the same experimental conditions. This indicates that surface roughness variations become more pronounced as wear progresses, reinforcing the influence of spindle degradation on machining outcomes. Also, the clusters for even number slots have a higher dispersion, this highlights the influence of spindle speed on the surface roughness results.

The combined analysis of spectral content, statistical feature extraction, correlation analysis, and PCA provides valuable insights into the effects of bearing wear, unbalance, and machining conditions on both vibration behaviour and surface roughness. The spectral analysis confirms the presence of bearing defects and system dynamics, while PCA results indicate how specific vibration features relate to surface quality. This study demonstrates that higher wear levels increase variability in machining outcomes, underscoring the importance of condition monitoring for maintaining machining stability. However, further validation through additional experiments is needed to minimize the impact of uncertainty factors on measurements.

5. Conclusion and future outlook

This study investigates the relationship between spindle errors and machining quality. It introduces an ESU as a flexible and controlled platform for testing machining operations, allowing for the injection of known errors such as bearing wear, unbalance, and mechanical looseness. The experimental setup allowed for a systematic evaluation of how spindle degradation affects machining performance, particularly in terms of vibrational response and surface roughness quality.

Spectral analysis revealed that bearing damage characteristic frequencies were clearly identifiable, with harmonic behaviour strongly influenced by cutting conditions. The statistical feature analysis confirmed that vibration parameters such as Kurtosis, Crest Factor and Standard Deviation showed clear trends with increasing spindle degradation, while roughness parameters such as Rku, Rmr and Rz exhibited strong correlations with the machining stability. The PCA further highlighted these relationships, showing that specific vibration features align with roughness parameters, confirming their relevance for condition monitoring. PCA projections also showed progressive dispersion of clusters with increased wear, indicating higher variability in surface quality as spindle degradation progresses.

The ESU proves to be a valuable tool for studying spindle degradation and its effects on machining performance, offering insights for predictive maintenance. Future work will explore additional degradation mechanisms, such as thermal effects and lubrication loss, and integrate machine learning models to enhance predictive capabilities. Real-time monitoring and adaptive control strategies will also be considered to improve industrial applicability.

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