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Progression of Cutting Tool Wear and Vibration Emission in the Grinding Process

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ABSTRACT

This study investigates the progression of cutting tool wear in grinding by analysing vibration emissions. The measurement was conducted under a repeated single operating condition. A cylindrical carbon steel workpiece was ground using a CNC grinding machine with coolant. Vibrations were measured along the X, Y, and Z axes using a Dytran 3-axis piezoelectric accelerometer, with data collected via NI DAQ 9234 at 12.8 kHz. A total of 70 grinding cycles were performed at 3000 rev/min (50 Hz). Root mean square (RMS) values of vibration signals were extracted as well as kurtosis, skewness and variance, to evaluate the correlation between tool wear progression and vibration characteristics. The findings highlight the sensitivity of vibration response to gradual tool wear. This study demonstrates the potential of using vibration measurement as a reliable indicator for monitoring grinding performance, improving process stability, and enhancing product quality.

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INTRODUCTION

One of the most adaptable machining techniques, grinding is utilised extensively in the automotive, aerospace, and tooling sectors to achieve tight tolerances and high-precision surface finishes. Many industries require different precision levels, with automotive components normally having lower tolerance compared to aerospace applications, which demand much tighter tolerances. In order to remove material, a spinning grinding wheel with abrasive grains embedded in it interacts dynamically with the workpiece [1]. However, because of the intricate relationships between the grinding wheel, workpiece, and machine parts, grinding is inevitably linked to vibration emissions even with its precision reflected in the outcome product. Surface quality, tool longevity, and machining performance are all greatly impacted and shown through the emitted vibrations. Vibration analysis is an essential component of process optimisation since vibration characteristics change as tool wear advances over time [2]. Gaining an understanding of the vibration emissions helps save production costs, increase tool life, and improve control over machining accuracy.

In grinding processes, vibrations come from both self-excited and forced sources. Machine imbalances, misalignments, or abnormalities in the grinding wheel can cause forced vibrations from the outside [3]. Conversely, self-excited vibrations, sometimes referred to as chatter, are frequently the cause of dynamic instabilities and arise from a feedback loop between the tool and the workpiece. Vibration amplitudes and frequency characteristics change as the grinding wheel wears down, allowing vibration analysis to measure the course of tool wear. In order to lessen the negative consequences of these vibration behaviours, it is possible to optimise crucial process parameters including speed, feed rate, and depth of cut.

Monitoring and analysing vibrations in grinding processes is now much easier because of developments in sensing technologies (e.g., vibration sensor, acoustics sensor, temperature sensor). While non-contact techniques like laser Doppler vibrometers offer further measurement options, high-resolution accelerometers are frequently employed to collect vibration data [4]. Raw vibration data can be processed using signal processing techniques such as envelope detection, wavelet analysis, and Fourier Transform to derive useful diagnostic information [5]. Furthermore, depending on intricate vibration patterns, machine learning algorithms are being utilised more and more to forecast and categorise tool wear [6, 7, 8]. These developments allow for real-time decision-making for process optimisation and improve the precision of tool status monitoring.

The purpose of this study was to examine how vibration emissions from grinding under single grinding operating condition as cutting tool wear. The vibration behaviour due to the grinding operations was examined for the relationship between tool wear and vibration characteristics through the analysis of r.m.s. magnitude of acceleration, skewness, kurtosis, and variance.

METHODOLOGY

This study focuses on evaluating the vibration characteristics generated during the grinding process. The experimental procedure was straightforward to ensure clarity and reproducibility. In this study, the process involves grinding the workpiece, measuring the resulting vibration signals, and analyzing the data based on RMS acceleration, variance, and kurtosis to assess tool and surface interaction behaviour

Cutting Tool and Workpiece Material

In this study, the cutting tool was a grinding wheel which used to grind a slightly larger 10mm diameter cylindrical workpiece. The workpiece has a material of cobalt. The grinder grinds the workpiece cylindrically to achieve exactly 10 mm diameter of workpiece. The complete process involves diameter operations and finishing which combined of a total of 4 phases.

Experimental Setup

A CNC Grinding machine was employed for the grinding operation. The grinding process was carried out in wet machining conditions (with coolant). One Dytran 3-axis Piezoelectric Accelerometers (100mV/g) were installed and positioned on the tool holder as shown in the Figure 1, to measure vibrations along the X, Y, and Z axes. A data acquisition device, the NI DAQ 9234, was used for data collection at 12800 samples per sec. A single grinding process took about 6 minutes to complete at 3000 rev/min (50 Hz) before the next workpiece was reinserted into the workpiece holder. This measurement has employed 70 cylindrical workpieces.

Analysis

This study uses MATLAB to process the vibration signals using both time-domain and frequency-domain analyses. The vibration data were also evaluated based on root mean square (RMS) acceleration, skewness, kurtosis, and variance. A total of 70 datasets were analysed in this study.

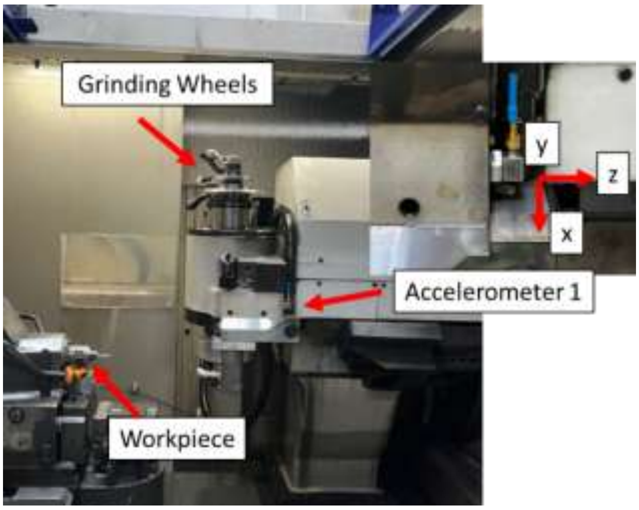

Figure 1. The experimental setup of the study.

RESULTS AND ANALYSIS

Time domain and frequency domain analysis of a single measurement

Figure 2 shows an example of the time-domain vibration measured throughout the grinding process for a single workpiece which accounted the grinding process. The vibration in the Z-axis exhibited the highest amplitudes compared to the Y and X-axes. The higher vibration in the Z-axis was likely due to the grinding force acting mainly in that direction, which was parallel to the workpiece surface. This caused more vibration energy along the Z-axis compared to the X and Y axes. The strongest vibration response was observed during the initial 150 seconds, after which the vibration intensity gradually decreased, becoming relatively flat beyond 300 seconds.

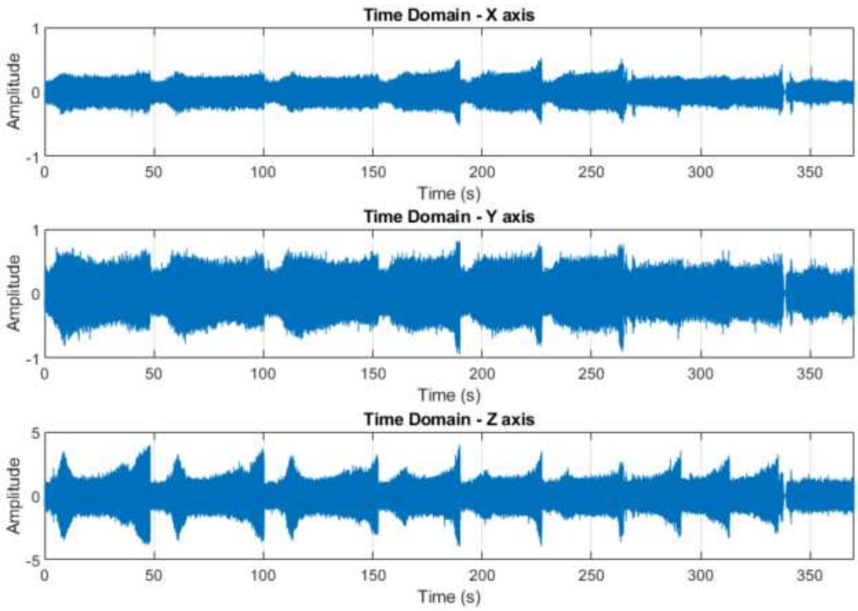

Figure 2. Time domain vibration of a single dataset.

Figure 3 shows the frequency spectra of vibration signals along the X, Y, and Z axes during the grinding process of a single dataset. Several dominant peaks are observed and visible at distinct frequency bands, indicating periodic vibration responses associated with machine rotation and wheel–workpiece interactions. In the X-axis, significant peaks occur mainly at lower frequencies below 3000 Hz, reflecting impulsive events and structural responses caused by wheel wear and contact instabilities. The Y-axis also shows multiple strong peaks, with slightly higher amplitudes compared to the X-axis, suggesting that lateral vibrations are more sensitive to wheel–workpiece interactions. The X and Y axes showed similar amplitude patterns because both represent radial directions of the grinding wheel in comparison with the Z-axis. In contrast, the Z-axis spectrum exhibits a distinct concentration of energy between 4000–6000 Hz. This may indicate that the vibrations are more strongly influenced by high-frequency dynamics which can be due to grit fracture, abrasive impacts, and continuous tool–workpiece contact as it was in the direction where grinder apply the load. This observation highlights the importance of multi-axis monitoring for reliable condition assessment and improved understanding of grinding dynamics.

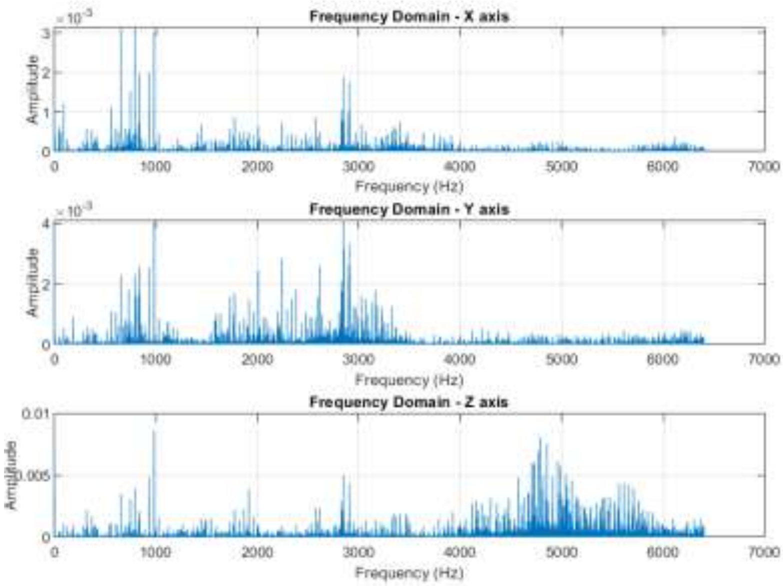

Figure 3. Frequency domain vibration of a single dataset.

R.M.S. acceleration of the grinding wheel

The trends of RMS acceleration in the X, Y, and Z directions are illustrated in Figure 4. The study found that the trend of vibration acceleration progressively changes in tool condition during the grinding process. Along the X-axis, RMS values rise steadily from ~0.065 to ~0.075, indicating an increase in vibration levels as the grinding wheel wears and cutting interactions become more irregular. A similar pattern is observed in the Y-axis, where values grow from ~0.13 to ~0.145 before it became relatively stable after about the 30th workpiece, suggesting that the tool enters a relatively steady wear phase. Both X and Y-axis shows a more uniform pattern because of the radial components of the grinding wheel, where the vibration response was expected to be increased more consistently with wheel wear compared to the Z-axis.

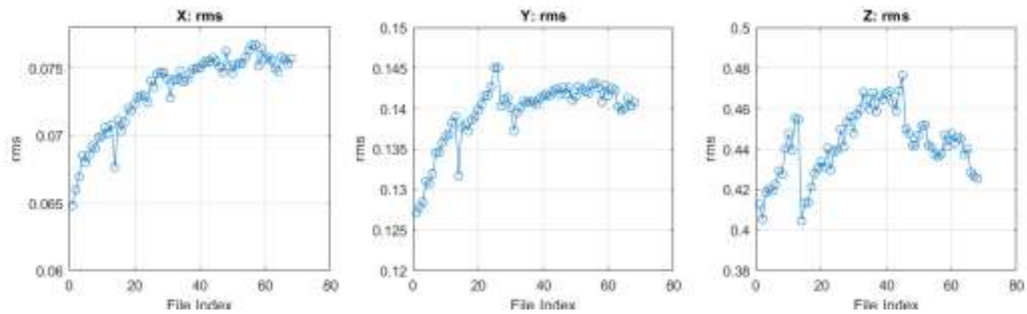

Figure 4. R.M.S acceleration of all 70 datasets.

In contrast, the Z-axis vibrations initially increase but then decline after approximately the 45th workpiece. This suggests that while early wear amplifies vertical vibrations, later stages alter the contact mechanics, potentially reducing vibration transmission in this direction. Overall, the figure confirms that RMS values are sensitive to tool wear, with each axis displaying distinct dynamics that highlight the anisotropic nature of grinding forces.

Variance of vibration measured on the grinding

Figure 5 presents the variance of vibration signals along the X, Y, and Z axes during the grinding process across all 70 datasets. In the X-axis, variance increases gradually and consistently with the number of workpieces. This indicates that a progressive rise in energy applied towards the workpiece as the grinding wheel wears. The Y-axis shows a similar upward trend although it came with some fluctuations and with less steadily compared to the X-axis. The Z-axis variance initially increases but then and lowers reflecting the dynamic variations in the wheel–workpiece contact.

These findings suggest that variance, as a measure of vibration amplitude spread, is sensitive to the gradual progression of tool wear and the evolving stability of the grinding process. Variance can provide a reliable feature for detecting tool wear progression and can be integrated with higher-order statistics such as kurtosis to enhance the robustness of vibration-based monitoring strategies.

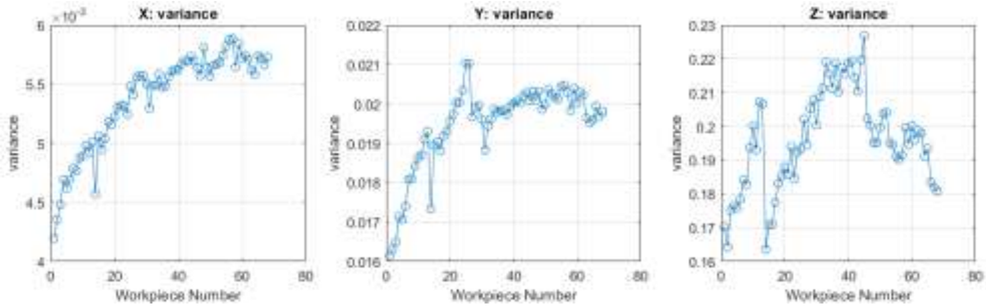

Figure 5. Variance in the acceleration of all 70 datasets.

Skewness of vibration measured on the grinding wheels

The skewness plots for the X, Y (Figure 6), and Z vibration signals provide insight into the asymmetry of the vibration distributions during the grinding process as the tool wear progresses. For the X-axis, skewness values generally maintained close to zero with several sharp negative drops, reaching as low as –0.25. These variations and fluctuations suggest irregularities in the vibration signal which likely caused by a sudden variation in grinding wheel-workpiece interaction.

For the Y-axis, the skewness changes from the negative values in the early cycles to positive values after approximately the 30th workpiece. This eventually reaching about 0.05. This observation indicates that the signal becomes increasingly dominated by higher-amplitude deviations as tool wear progresses.

For the Z-axis, the vibration signals remain negatively skewed throughout, with values clustering between –0.02 and –0.07, suggesting that vibration signals along this direction consistently favour lower-amplitude deviations. Overall, the skewness results highlight directional differences in vibration asymmetry, thus requiring the need to evaluate multiple statistical features for comprehensive tool wear monitoring.

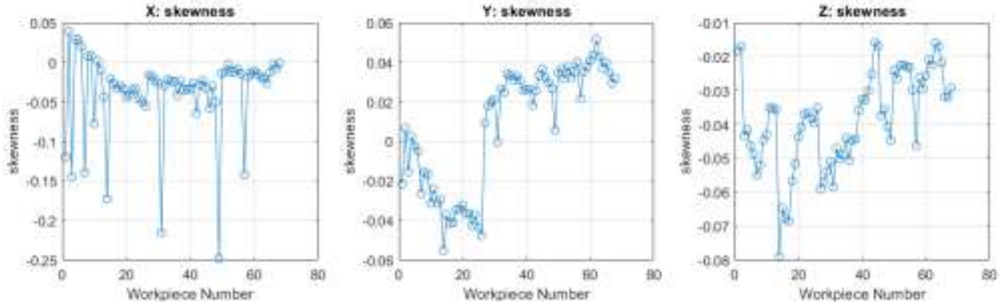

Figure 6. Skewness in the acceleration of all 70 datasets.

Kurtosis of the vibration measured at the grinding wheels

Figure 7 shows the kurtosis progression of vibration signals in the X, Y, and Z directions during grinding of the workpieces. Several large spikes were observed in the X-axis, indicating impulsive vibration may be caused by wheel wear, or grit fracture. The Y-axis on the other hand, presents relatively stable kurtosis values with only moderate fluctuations. In contrast, the Z-axis shows a steady upward trend in kurtosis, suggesting progressive and systematic tool wear in the normal grinding direction where contact forces are most dominant.

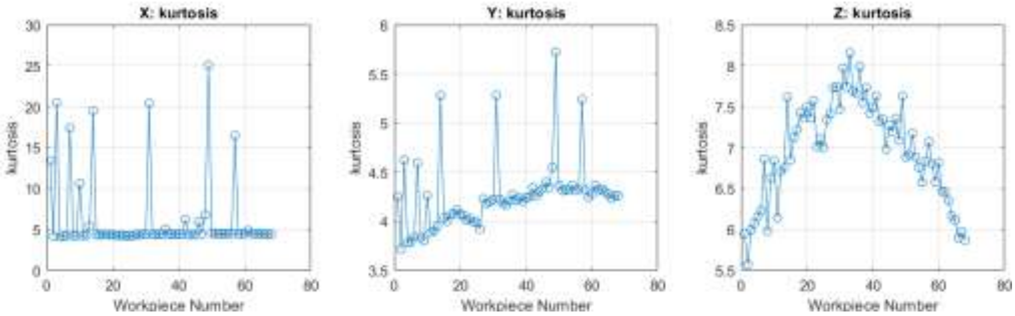

Figure 7. Kurtosis in the acceleration of all 70 datasets.

CONCLUSIONS

The multi-axis vibration analysis demonstrates that tool wear progression influences vibration characteristics differently across the X, Y, and Z directions. RMS, variance, skewness, and kurtosis each captured distinct aspects of the grinding process, confirming their effectiveness as complementary features for monitoring wheel condition. Together, these findings highlight the value of integrating multi-domain and multi-feature vibration analysis for reliable grinding wheel wear assessment and process stability evaluation.

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