Sound Analysis of Computer Numerical Control Machines Using AI Tools: Investigating Zero Crossing Rate Effects on the Environment

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Abstract – This article implements a sound analysis system using a technique for intelligence the difference in sound frequencies when operating a CNC milling machine. CNC machines technology generates sounds during any production process. In this study, using a microphone as a sound receiver, the software tools Librosa analyzed the sounds and then displayed the results on frequency and amplitude graphs to evaluate the sound quality in the mass production of CNC milling machines. We analyze the sound zero crossing rate (ZCR) and the Mel spectrogram audio data. By determining the frequency difference of the sound produced by the CNC machine in real time, it was indicated how it works to ensure environmental safety and technological processes.

Keywords – Sound Detection, CNC Milling Machine, Safety Indicator, Sound Analysis, Sound Zero Crossing Rate (ZCR).

I. INTRODUCTION

The advantage of modern technology of manufacturing has significantly enhanced the precision and efficiency of industrial processes. Among these one of technologies, Computer Numerical Control (CNC) machines use in various sectors, including aerospace, automotive, and electronics. Computer numerical control (CNC) is an automatic technology that uses a computer program to control mechanical tools [1]. Additionally, a CNC machine eliminates human mistake, resulting in a more reliable output. Compared to a conventional-manual operator, a CNC operator is farther away from the sharp tools. Additionally, this speeds up and lowers the cost of the entire production process. However, despite their wide usage, CNC machines generate noise during operation, which poses environmental and health concerns. In the recent years, the use of CNC machineries is rapidly increased. They produce sounds during operation times. A sound has different elements to analysis. Zero crossing rate (ZCR) one of them. Zero crossing rate (ZCR) is the rate within a given time frame at which a signal changes its sign from positive to negative or vice versa. Zero-crossing rate (ZCR) is one of the most crucial acoustic or sound features that has been utilized extensively in voice activity detection, voiced/unvoiced speech classification, music/speech classification and also used in image processing, optics, radar and fluid mechanics. On the other hand, Mel spectrogram is a method of graphically depicting the amplitude, or loudness, of a signal as it changes over time at various frequencies. The Mel spectrogram is a useful tool for audio analysis tasks since it can record the sound's spectral and temporal properties [2].

Artificial Intelligence (AI) tools, which have revolutionized numerous industries, offer promising solutions for noise analysis and management. A software program that employs artificial intelligence algorithms to carry out specific roles and resolve issues is known as an AI tool. Librosa is an audio processing library that is beneficial to researchers and music enthusiasts [3]. With its user-friendly interface and a wide range of functionalities, Librosa makes it easy to analyze and manipulate audio signals and audio data. Librosa is a python package for sound and audio analysis. It takes steps the building blocks necessary to create audio information retrieval systems. One key aspect of this is the Zero Crossing Rate (ZCR) – a fundamental metric used in the study of sound signals. ZCR represents the rate at which a sound signal crosses the zero axes, providing valuable insights into the characteristics of noise produced by CNC machines. By utilizing AI techniques to analyze ZCR, it is possible to gain a deeper understanding of how CNC machines emit sound and develop strategies for reducing their environmental footprint.

Zero Crossing Rate (ZCR) sound analysis of CNC machines is essential for minimizing the environmental effect of manufacturing operations. ZCR calculates the speed at which a sound signal passes zero amplitude, which may be a symptom of operational inefficiencies or mechanical irregularities in the equipment [4]. Artificial intelligence (AI) technologies that analyze ZCR can identify unusual noises or vibrations that indicate problems such as wear, misalignment, or unbalanced parts in CNC machines. By seeing these issues early on, AI makes predictive maintenance possible, guaranteeing that equipment is maintained before it breaks down, minimizing waste, and avoiding needless energy use. Energy efficiency and the decrease of noise pollution are two more environmental advantages of this approach. Through ZCR monitoring, artificial intelligence (AI) systems are able to identify when machines are running loudly or inefficiently, allowing for modifications that lower dangerous noise levels and safeguard wildlife and neighboring residents. AI-enhanced machine performance also saves energy and prolongs the machine's life, which translates into reduced material waste and fewer replacements. Thus, ZCR-based sound analysis promotes more environmentally friendly production methods, thereby reducing the overall environmental impact of CNC operations [5].

In this article, we analyze the zero crossing rates of different materials such as aluminium and wood. This article explores the application of AI tools in the sound analysis of CNC machines, with a focus on zero crossing rate and Mel spectrogram differences among above materials. However, in our future research we will find out the effective approaches for controlling and reducing the environmental impact of CNC machine noise, contributing to more sustainable manufacturing practices.

II. LITERATURE REVIEW

In the field of modern manufacturing, the advent of numerical control technology (CNC) has revolutionized production processes. Monitoring and ensuring the efficiency and quality of CNC machining operations is crucial to maintaining optimal performance. In the manufacturing sector, numerical control (CNC) machines are used to create parts or elements such as screws, bolts, nuts, and the required pattern according to our requirements. The CNC milling machine will make noises and vibrations [6], and depending on the pressure used, these vibrations will produce a particular frequency range. Additionally, the vibrations will serve as a gauge of how smoothly the milling process is going, and it can be used to determine whether the vibration is normal or if there is a chance of errors like balance, physical, or mechanical determination. In the industrial world, computer numerical control (CNC) [2] is a machine that is widely used to enable the manufacturing of things in the required shape and condition by entering pre-designed commands. The first step in the CNC's operation is to type the forms that need to be created straight onto a CNC machine or a PC pad using CNC programming software. The created order or program is then transmitted to a CNC machine, which completes the order process in accordance with the program and the required shape [7]. These vibrations will create a certain frequency range depending on the pressure used and will also serve as an indicator of how smoothly the milling process is going. Based on the vibrations during the process, it will be possible to determine whether they are normal or potentially abnormal. There may be errors in physical, mechanical, or balancing calculations.

Based on an understanding of acoustics and signal processing, the author describes how to identify a specific echo audio signal from sonar or human speech using sound detection built into software created as a graphical algorithm for detecting an echo signal in real time. In order to identify bearing wheel damage and prevent unplanned stoppages, P. Tanushka et al. [8] use sound signal analysis to perform anomaly detection and prediction for an assembly process maintenance system to the bearing wheel bearings. This analysis is assessed using frequency analysis and time-domain statistical indicators. One of the methods for determining the condition of the spindle bearings of a CNC machine is the analysis of noise signals during spindle operation, as demonstrated by the authors in this work [9]. Both indirect and direct detection methods are used. Because of this, the purpose of this simulation is to simulate the sound detection program in the software in order to control the milling process during machine operation [10]. In addition, Gok Arif et al. conducted the proposed experiment in order to understand the relationship between sound signals and surface roughness during the processing of inclined concave and convex surfaces. This study presents an innovative approach to the detection and classification of CNC milling sounds using audio analysis techniques [11]. Evaluation using experimental facilities and real-world scenarios demonstrates the effectiveness and potential of this approach in industrial applications, paving the way for more intelligent and responsive production environments. An examination of the sound field produced by specific CNC machine tools is given by this author [12]. Source identification and noise level are measured by acoustic holography for the five-axis vertical machine center DMU 65 Monoblock and the three-axis DMC 635eco machine tool. Identification and measurement are made possible using the acoustic holographic approach. Diagrams and graphics are used to present the study's findings. The purpose of this monitoring is to keep on the CNC milling process and determine whether it is operating smoothly or if there is a disruption so that the operator may learn about it [13]. The K-means algorithm will be used to classify the resonant signal frequency results from sound detection in order to distinguish between the resonant frequency signal and noise, making classification simpler. The K-means clustering results will then be plotted once more in Excel to provide a clear image.

The examination of acoustic signals in Computer Numerical Control (CNC) machines has been greatly improved by recent developments in artificial intelligence (AI). A deep learning-based system that evaluates sound inputs from industrial machinery was presented in a paper [14]. The system demonstrated the effectiveness of AI in fault identification inside CNC operations by converting auditory data into Mel spectrograms and using the DenseNet-169 model for classification. The accuracy rates ranged from 97.17% to 99.87% across a range of noise levels.

In sound analysis, the Zero Crossing Rate (ZCR), which gauges the frequency of signal amplitude sign changes, is a crucial component [15]. The AI-based program LibROSA was used in another paper to analyze ZCRs between musical sounds and mechanical sounds from CNC milling machines. According to the results, mechanical noises have greater ZCRs than musical ones, suggesting that ZCR is capable of accurately differentiating between various sound sources in CNC settings. In their study on the effects of CNC machining on the environment, authors stressed the significance of sustainable practices [16]. They emphasized how environmental degradation is exacerbated by CNC techniques' excessive energy consumption and material waste. Essential tactics to lessen these effects include implementing eco-friendly practices, optimizing material utilization, and putting energy-efficient technologies into place. By combining environmental concerns with technology improvements, the study promotes a holistic approach to sustainability in CNC operations [17].

III. RESEARCH METHODOLOGY

In our article, we combined the zero-transition rate (ZCR) and the Mel spectrogram. The zero transition rate (ZCR) is an important parameter used as part of external processing in an automatic speech recognition system. The number of transitions through zero is an indicator of the frequency at which the energy in the signal spectrum is concentrated. Voiced speech leads to a small number of transitions through zero [9], while silent speech leads to a large number of transitions through zero.

A Mel spectrogram is a type of spectrogram that is commonly used for speech processing and mass learning. It is similar to a spectrogram in the sense that it shows the frequency composition of an audio signal over time, but on a different frequency axis. We have collected audio data obtained during the operation of a CNC milling machine for cutting aluminum and wood. Different audio signals display different ZCR values (zero crossing rates) and mel spectrograms [18]. According to our research, there are stages of input, analysis and output in the flowchart. We use a microphone for input and record the sound for about a minute. That's why I use sounds for analysis using LibROSA software tools. The library is a large-format sound analysis toolkit based on intelligent intelligence. At the end of the analysis, we will know the output results [19].

Proposed Block Diagram of Sound Detection Monitoring tool for CNC Milling

A block diagram of a sound detection monitoring and analysis system is depicted in **Fig 1**. In this figure, the block diagram of the experiment represents the experimental system and its execution. The detection of the sound of CNC milling machine recorded by a microphone will be programmed and classified using the cluster machine learning method.

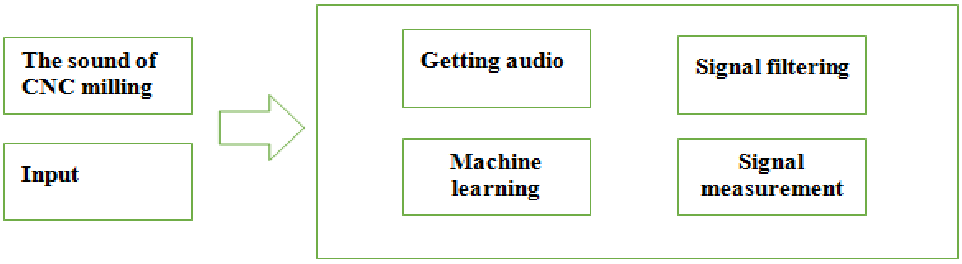

Fig 1. Diagram of Sound Detection.

Flowchart Implementation

Fig 2 shows the flow chart of the experimental procedure and shows the order of sound collection, signal filtering, and resonance frequency analysis in real time. After starting the CNC machine, the frequency of sounds will be generated, and then transmit the sounds obtained by the CNC machine to the system audio microphone recorder. The flowchart describes a process for analyzing sound generated by a CNC milling machine, likely for quality control or machine health monitoring. The related algorithm is mentioned in the following which depicts a step-by-step approach:

Algorithm

1. Start: Initiates the process.

2. CNC milling sound: The CNC machine is operational, producing sound during milling.

3. CNC for acquisitions: The system attempts to acquire sound data from the CNC machine.

4. Decision (Yes/No): Checks if the sound data was successfully acquired.

- No: Loops back to retry data acquisition.
- Yes: Proceeds to the next step.
5. Receive: The acquired raw sound signal is received for processing.
6. Filtered signal: Noise or irrelevant frequencies are removed from the raw signal.
7. Measurement: Key parameters (e.g., amplitude, duration) are measured from the filtered signal.
8. Frequency: Specific frequency components of the sound are analyzed (critical for detecting anomalies or tool wear).
9. Result: The outcome is generated (e.g., "normal operation," "tool replacement needed," or frequency values).
10. End: The process concludes.

This workflow ensures consistent monitoring of CNC machine performance by analyzing acoustic data, with retries for failed data acquisition and steps to derive actionable insights.

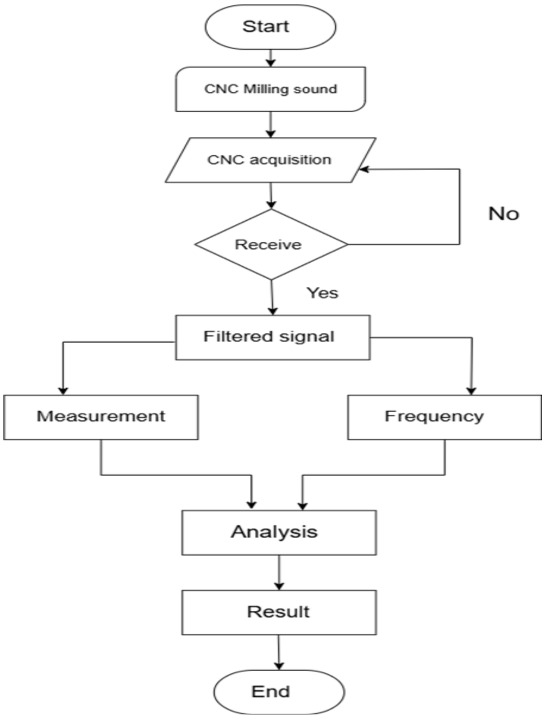

Fig 2. Proposed Block-Diagram.

IV. ANALYSIS AND DISCUSSION

In this section, at first the hardware acquisition system using the sound detection method is designed where sound is transmitted from microphone to computer through Librosa tool. Various mathematical formulas are discussed here for proper and efficient sound analysis.

Hardware Acquisition System using Sound Detection

The hardware system diagram for the experimental setup is shown in **Fig 3**. The integration system uses sound detection software created in Librosa to detect the resonant frequency of each sound produced during the CNC milling operation. The microphone is a type of receiver that records sound waves on a recording medium or converts them into electrical signals. Librosa is the sound analysis tool. The computer is used to visualize the data, present the results, and monitor changes.

Fig 3. The Structure of Hardware Systems.

- CNC milling procedure and related forms of operations for the parameters of the analysis range in units of measurement (Hz).
- Sound acquisition by data acquisition Audio equipment can be used to receive audio data (Realtek high-definition audio microphone) on channel 1 for 5 or 6 seconds with a resolution of 16 bits.

- The amplitude function is used in combination with spectral measurement. Peak values at the resonant frequency are used to quantify the amplitude of the spectrum. If the average value is marked as linear, the phase of the spectrum is set to zero. To determine the frequency, range of a single node with the maximum amplitude, the tone measurement is evaluated.
- The Port Audio v19 cross-platform audio I/O package has Python bindings available through LibROSA. Python has been used to play and record audio on a number of operating systems, including GNU/Linux, Windows, and Apple macOS, using LibROSA. It is released under the terms of the MIT license.

The Amplitude Formula

A variable's largest deviation from its mean value is referred to as its amplitude. The sine and cosine functions can be found using the amplitude formula. A is a representation of amplitude. One way to express the sine or cosine function is as follows: Below is the formula used to calculate the amplitude in **Fig 4,**

$$x = A \sin(\omega t + \phi) \tag{1}$$

Here,

- x = this is the offset in meters
- A = amplitude
- ω = angular frequency in radians/s
- t = this time in seconds
- ϕ = phase shift in radians

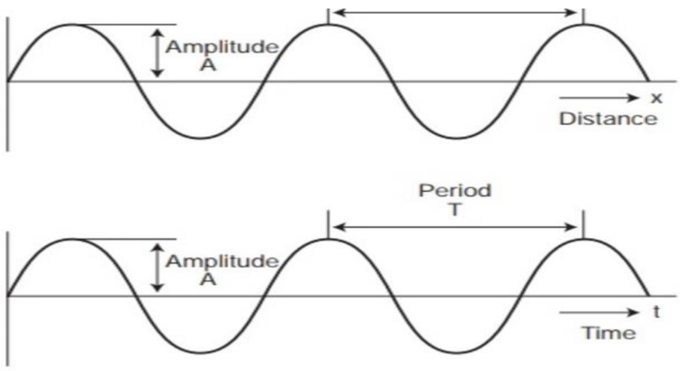

Fig 4. Amplitude vs. Time [Source: https://www.brainkart.com/article/Characteristics-of-a-sound-wave_39936]

Determining the number of zero crossings in a signal segment is a relatively simple way to assess how smooth the signal is. A silent fricative sound can have up to 3,000 zero crossings per second, but the voice signal fluctuates slowly—for example, a 100Hzsignalwillcrosszero100timespersecond. The implementation of the zero transition control of the x that signal in the K window is

$$ZCR_{\bar{k}} \sum_{h=kM}^{kM} |sign\ (x_h) - sign(x_h - 1)\,| \tag{2}$$

Where M is the step between the analysis windows, and N is the length of the analysis window.

To calculate the frequency at which a zero value is crossed by a signal, you need to compare the sign of each pair of consecutive counts. In other words, for a signal of length N, you need O(N) operations. Such calculations are also extremely easy to implement, which makes the zero-crossing coefficient an attractive indicator for low-complexity applications [20]. The CNC milling machine makes a sound while cutting aluminium in the **Fig 5** showed aluminium plate and CNC machine.

Fig 5. CNC Milling Machine for cutting Aluminium. [Source: https://www.istockphoto.com/photos/cnc-aluminium].

To collect data for aluminium cutting, we record the sound of aluminium cutting from a CNC milling machine using our system sound recorder in WAV format that are shown in **Fig 5**. We then implement AI-based machine learning algorithms to extract beats using LibROSA tools. We determine the time domain frequency (amplitude), the zero-crossing frequency of sounds in milliseconds, the sampling frequency of the duration of sounds, and their time duration. The information is provided in the **Table 1** below. Here we take 6 different frequency data from 1–7000, 7000–14000, 14000–21000, 21000–28000, 28000–35000, and 1–1100000. We find different zero crossing frequencies according to 1040, 1073, 583, 1766, 2708, and 402490. Where the sampling frequency of the sounds is the same, which is 22050, and the duration is 82 seconds. According to the total duration of the sound, our time domain amplitude frequency is 1874250, and the total zero crossing frequency is 692484.

Table 1. Sound Characteristics of CNC Milling Machine for Cutting Aluminium

Time interval frequency (amplitude)	Zero Crossing Speed (ZCR)	Sampling Frequency	Time Duration (seconds)
1 - 7000	1040	22050	82 Seconds
7000- 14000	1073		
14000 - 21000	583		
21000 - 28000	1766		
28000 - 35000	2708		
1 - 1100000	402490		
Total = 1874250	Total = 692484		

Frequency amplitude time interval from 1 to 1100000, we get the following **Fig 6** for the sound when milling plastic and aluminum with CNC depending on the amplitude (Hz) and time.

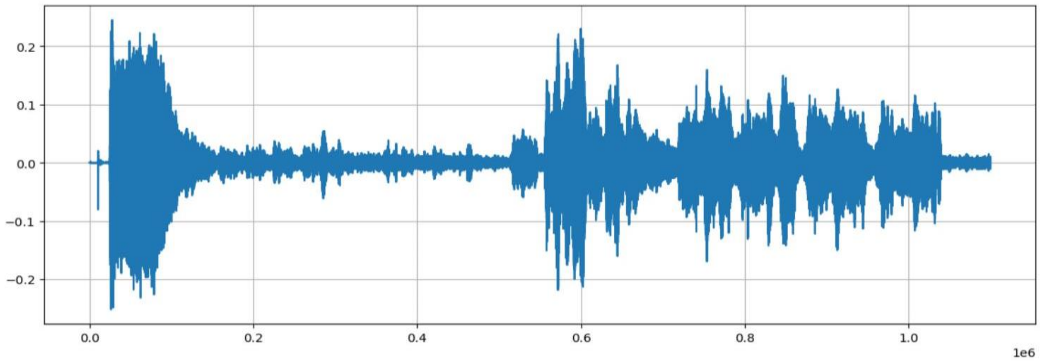

Fig. 6. Data on the Time and Amplitude of Sound When Cutting Aluminum.

Tempo is a unit of measurement of beats, where a beat is the basic unit of time. Approximate tempo: 92.29 bpm in our CNC aluminum milling sound tool. Here the total beat time is 122, and the arrays values are,

[0.510839 1.16099773 1.81115646 2.48453515 3.13469388 3.78485261
4.43501134 5.08517007 5.7353288 6.36226757 6.98920635 7.63936508
8.28952381 8.93968254 9.61306122 10.26321995 10.91337868 11.56353741
12.21369615 12.86385488 13.53723356 14.21061224 14.83755102 15.48770975
16.13786848 16.78802721 17.43818594 18.08834467 18.7385034 19.38866213
20.03882086 20.68897959 21.33913832 21.98929705 22.66267574 23.31283447
23.9629932 24.61315193 25.26331066 25.89024943 26.54040816 27.19056689
27.88716553 28.53732426 29.18748299 29.81442177 30.44136054 31.06829932
31.6952381 32.29895692 32.92589569 33.57605442 34.22621315 34.87637188
35.52653061 36.17668934 36.80362812 37.45378685 38.10394558 38.75410431
39.40426304 40.07764172 40.72780045 41.37795918 41.981678 42.58539683
43.23555556 43.86249433 44.4429932 45.06993197 45.69687075 46.37024943
47.06684807 47.74022676 48.4368254 49.13342404 49.83002268 50.50340136
51.17678005 51.85015873 52.47709751 53.05759637 53.7077551 54.33469388
54.96163265 55.58857143 56.2155102 56.84244898 57.49260771 58.11954649
58.79292517 59.4430839 60.09324263 60.76662132 61.44 62.06693878
62.69387755 63.34403628 64.01741497 64.69079365 65.34095238 65.99111111
66.64126984 67.29142857 67.96480726 68.63818594 69.26512472 69.96172336
70.63510204 71.30848073 72.00507937 72.701678 73.35183673 74.02521542

74.62893424 75.23265306 75.83637188 76.46331066 77.13668934 77.81006803
78.48344671 79.1568254], [122]

In the **Fig 7**, RMS (root mean square) is a mathematical term used to measure the average loudness of a sound wave. It's used in audio production, speakers, and electrical current analysis. In our **Fig 7** we used Librosa AI based tools for RMS calculation to CNC Router Sound Data during Cutting Aluminum.

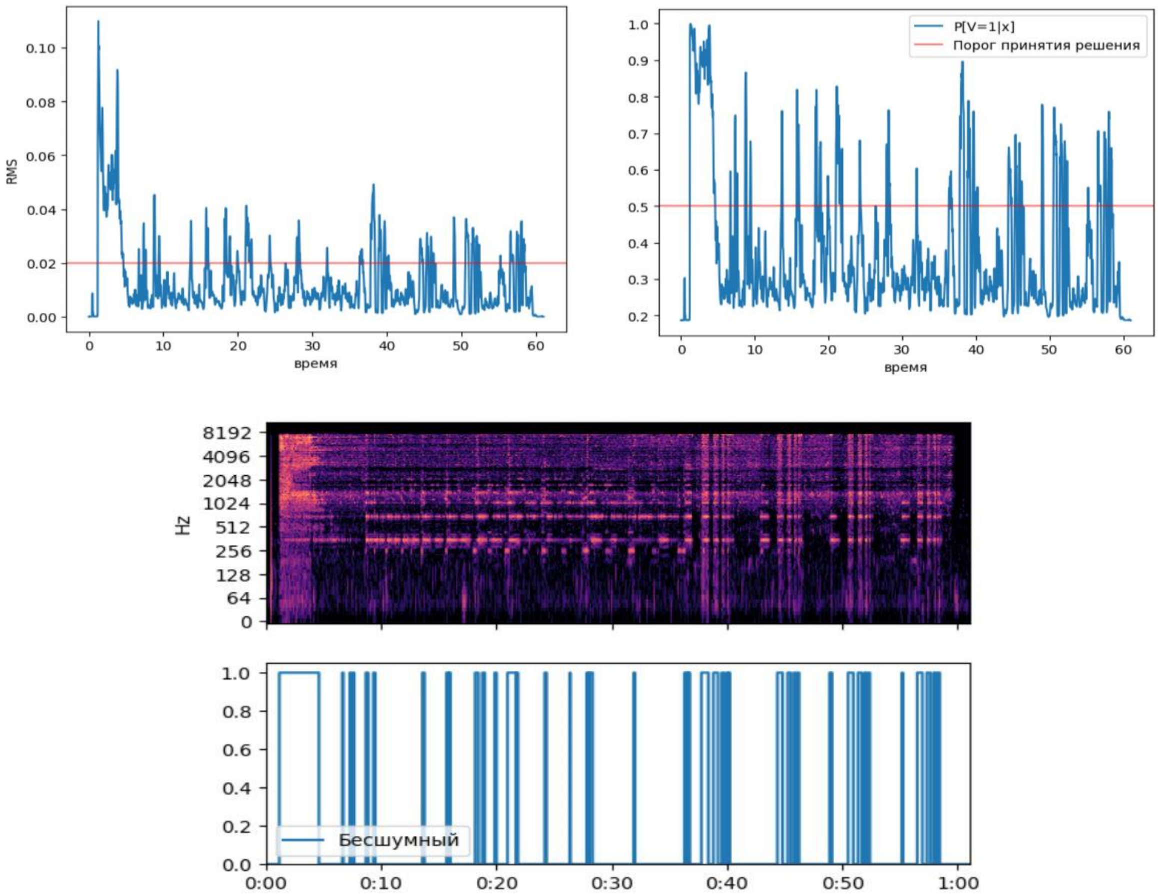

Fig 7. CNC Router Sound Data for Cutting Aluminum for RMS.

Wood Cutting
CNC Router Makes Sound When Cutting Wood that are shown in **Fig 8**.

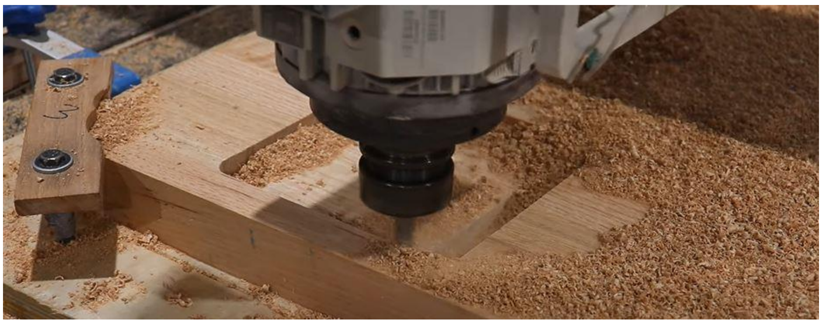

Fig 8. CNC Milling Machine for Cutting Wood. [Source: https://www.istockphoto.com/photos/cnc-wood].

To collect the data during wood cutting, we record the wood cutting sound from the CNC router with our system sound recorder in WAV format [21]. We then implement AI-based machine learning algorithms to extract the beats using LibROSA tools. We determine the time domain frequency (amplitude), the zero-crossing frequency of the sounds in milliseconds, the sampling frequency of the sound duration, and their time duration [22]. The information is provided in the **Table 2** below. Here we take 6 different frequency data from 1–7000, 7000–14000, 14000–21000, 21000–28000, 28000–35000, and 1–1100000. We find different zero-crossing frequencies according to 1153, 754, 876, 1487, and 2532, where the sampling frequency of the sounds is the same, which is 22050, and the duration is 72 seconds [23]. According to the total duration of the sound, our time domain amplitude frequency is 1543500, and the total zero crossing frequency (ZCR) is 465375 in the **Table 2**.

Table 2. Sound Characteristics of CNC Wood Cutting Machine

Time interval frequency (amplitude)	Zero Crossing Speed (ZCR)	Sampling Frequency	Time Duration (seconds)
1 - 7000	1153	22050	72 Seconds
7000 - 14000	754		
14000 - 21000	876		
21000 - 28000	1487		
28000 - 35000	2532		
1 - 1100000	326593		
Total = 1543500	Total = 465375		

Frequency amplitude of the time interval from 1 to 1100000, we get the following **Fig 9** for the sound of CNC wood milling depending on the amplitude (Hz) and time.

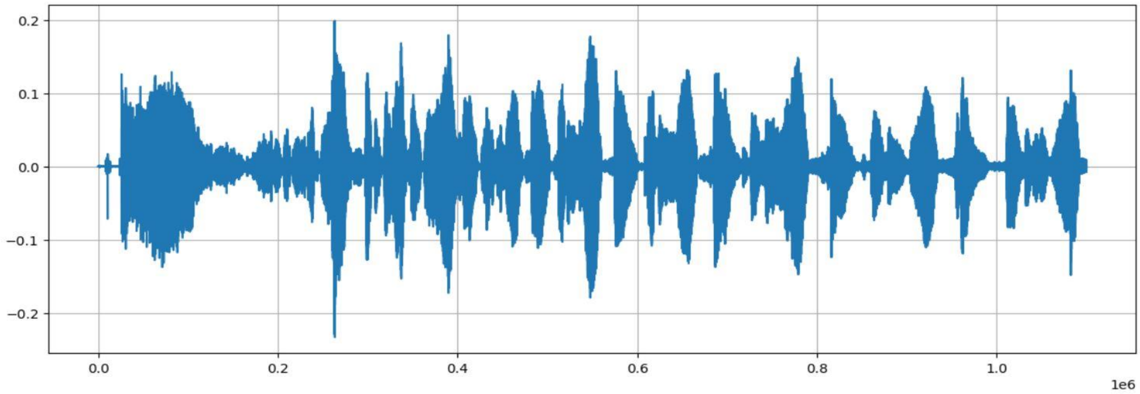

Fig 9. Data on the Time and Amplitude of Sound When Cutting Wood.

Tempo is a unit of measurement of beats, where the beat is the basic unit of time. Suggested tempo: 152 beats per minute in our CNC wood router sound tool. Here the total beat time is 176, and the arrays values are,

[0.11609977 0.510839 0.85913832 1.20743764 1.60217687 1.9969161
2.39165533 2.78639456 3.18113379 3.57587302 3.97061224 4.38857143
4.78331066 5.17804989 5.57278912 5.96752834 6.36226757 6.7570068
7.15174603 7.54648526 7.94122449 8.33596372 8.73070295 9.12544218
9.52018141 9.91492063 10.30965986 10.70439909 11.09913832 11.49387755
11.88861678 12.30657596 12.72453515 13.16571429 13.60689342 14.07129252
14.53569161 14.95365079 15.32517007 15.7199093 16.11464853 16.53260771
16.95056689 17.36852608 17.76326531 18.15800454 18.55274376 18.92426304
19.29578231 19.66730159 20.08526077 20.50321995 20.92117914 21.31591837
21.7106576 22.10539683 22.50013605 22.89487528 23.31283447 23.77723356
24.2184127 24.65959184 25.03111111 25.40263039 25.79736961 26.16888889
26.56362812 27.00480726 27.42276644 27.84072562 28.23546485 28.63020408
29.04816327 29.46612245 29.88408163 30.32526077 30.76643991 31.18439909
31.55591837 31.9506576 32.34539683 32.74013605 33.13487528 33.52961451
33.92435374 34.29587302 34.69061224 35.08535147 35.4800907 35.87482993
36.26956916 36.66430839 37.05904762 37.4770068 37.87174603 38.26648526
38.66122449 39.05596372 39.42748299 39.82222222 40.1937415 40.58848073
40.98321995 41.37795918 41.74947846 42.14421769 42.51573696 42.88725624
43.28199546 43.65351474 44.04825397 44.4429932 44.83773243 45.23247166
45.60399093 45.9755102 46.34702948 46.74176871 47.13650794 47.53124717
47.92598639 48.32072562 48.71546485 49.11020408 49.50494331 49.89968254
50.29442177 50.66594104 51.06068027 51.4554195 51.85015873 52.24489796
52.63963719 53.03437642 53.42911565 53.80063492 54.1721542 54.54367347
54.91519274 55.28671202 55.68145125 56.07619048 56.47092971 56.86566893

57.26040816 57.65514739 58.04988662 58.44462585 58.83936508 59.23410431
59.62884354 60.04680272 60.4647619 60.85950113 61.25424036 61.64897959
62.04371882 62.461678 62.85641723 63.25115646 63.62267574 64.01741497
64.4121542 64.80689342 65.20163265 65.59637188 65.99111111 66.38585034
66.78058957 67.1753288 67.54684807 67.91836735 68.33632653 68.75428571
69.14902494 69.54376417], [176]

Here again to find out differences RMS for wood cutting are showed In the Fig 10, RMS (root mean square) is a mathematical term used to measure the average loudness of a sound wave. It's used in audio production, speakers, and electrical current analysis. In our **Fig 10** we used LibRosa AI based tools for RMS calculation to CNC Router Sound Data during Cutting wood.

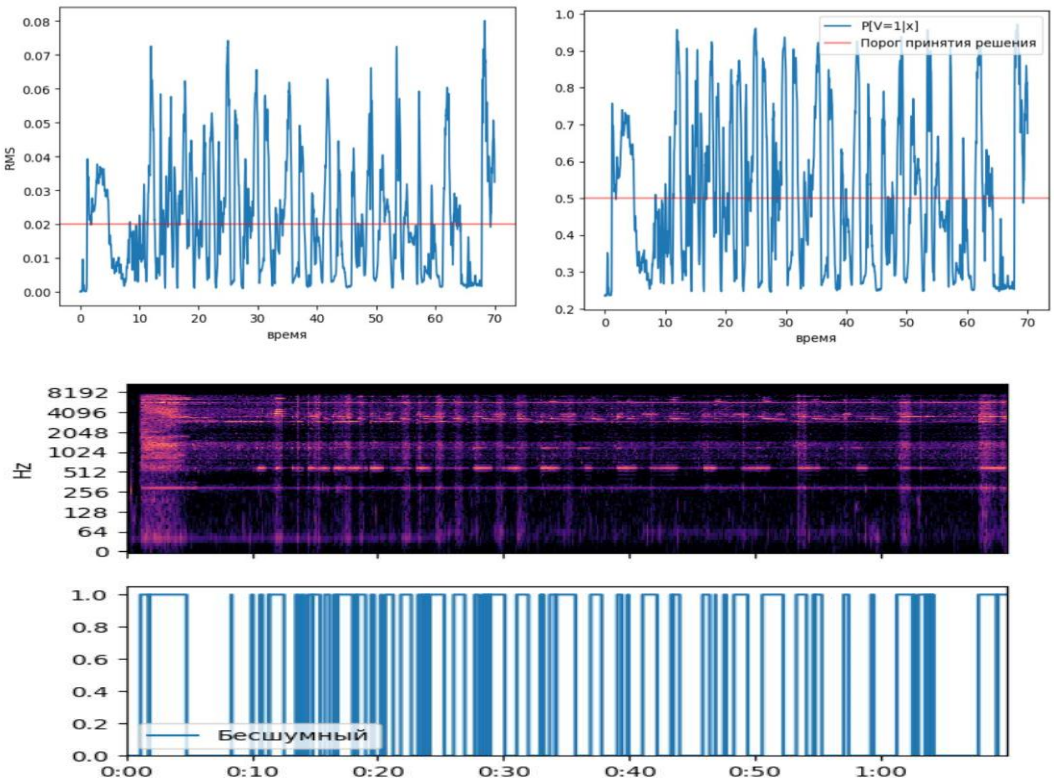

Fig 10. Sound Data of CNC Wood Cutting Router for RMS.

The following **Fig 11**, the sounds captured by our PyAudio analysis systems for a machine learning experiment. To conduct the experiment, the sound produced by the CNC machine is first converted into a digital signal using a microphone. The sound is filtered using the resonant frequency determined by the spectral measurement. The real-time measurement results show the tones, including amplitude and frequency.

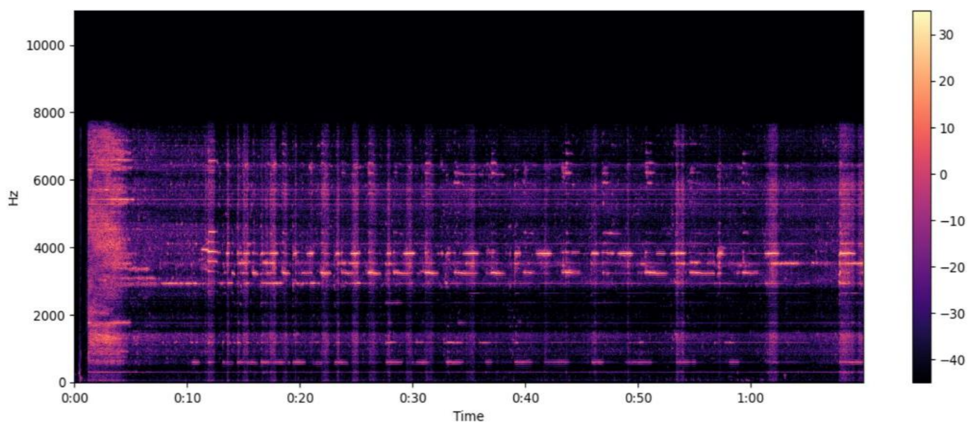

Fig. 11. On the Mel Spectrogram, The X-Axis Is Time, and the Y-Axis Is Its Frequency in Hz.

In the Mel spectrogram of the CNC router sound shown in the figure, there are shadows of different colors, such as orange, dark, and ash. The orange shadow indicates a high density of sounds. The ash color indicates that the sounds are present but with less density. The dark color indicates that the density of sounds is very low, and no sounds are heard for a while. In this figure, we notice the difference in the density of high, medium, and low sound frequencies. The figure shows that the amplitude of the generated sounds decreases over time. The Mel spectrogram for the aluminum CNC router shown in **Fig 6** shows more orange and ash colors. On the other hand, in the wood CNC router shown in **Fig 9**, the sounds were less orange and darker.

V. RESULTS

Librosa software and system integration use the parameters to adjust the stable resonance information, and the implemented analysis is applied to the experiment as a filter waveform **Table 1** and **Table 2**. The sampling frequency in both tables is the same at 22050, and we use our 5 times experimental report for the difference of 7000 Hz to determine the zero crossing frequency (ZCR). For the aluminum CNC milling, the cutting data is shown in **Table 1** the minimum ZCR is 583 with the amplitude range of 14000-21000 Hz. The maximum ZCR is 2708 with the amplitude range of 28000-35000 Hz. **Table 2** shows the wood cutting CNC milling machine data; the minimum ZCR is 745, where the amplitude range is 7000-14000, which shows that the embedded system is able to recognize the frequency change; it can measure both the amplitude and the resonant frequency. We can monitor the sound protection level that is comfortable for humans. The frequency of sounds is specified in different systems or in the machine and monitoring the difference in the frequency of sounds shows us that the machines have some technical problems. Under the same amplitude range of 1 to 1100000 Hz, the performance of the ZCR 402490 CNC aluminum cutting machine is higher than that of the ZCR 326593 wood cutting machine.

VI. COMPARATIVE ANALYSIS

Some notable differences between the research publications currently in publication and our work on Sound Analysis of CNC machines using AI tools and its ZCR effects on the environment—which will be discussed in the comparative analysis section—can be seen from the discussion of this paper above. Sincerely, the study findings over the past 10 years (2015–2025) in this field are needed to complete this task. The limitations of traditional approaches that only concentrate on progressive and predictable wear patterns are addressed in a research study by designing a sound-oriented tool-wear observational scheme. With the aid of the Tree Bagger machine-learning algorithm, the suggested system uses inexpensive, high-frequency microphones and sophisticated signal processing—which includes analog/digital filtering, oversampling, signal conditioning, PLL-based synchronization, and feature extraction (ZCR, RMS)—to record acoustic emissions during machining. The authors of a different study used time series sequential data, for which LSTM is the most effective method. It goes on to describe the potential and remarkable outcomes of deep learning with Long Short-Term Memory Networks (LSTM) and acoustic data recorded by a microphone during the metallic milling process [23].

The zero crossing rates of various materials, including wood and aluminum, are examined in our study. The use of AI techniques to CNC machine sound analysis is examined in our article, with particular attention paid to zero crossing rate and variations in Mel spectrograms among the materials mentioned above [24-26]. In order to do this effectively, a relevant algorithm is proposed along with mathematical simulation as well as implementation are depicted throughout our paper. But in our next studies, we'll learn how to effectively manage and lessen the noise produced by CNC machines, which will help us adopt more environmentally friendly production methods.

VII. CONCLUSION

The integrated system identified the resonance frequency and sound amplitude values in the CNC milling process in real time based on the testing results. Its sensitive recognition of the sounds emitted by CNC machines can distinguish between high and low frequencies. The interference in the signal causes the operating points related to the resonance frequency and amplitude to monitor the CNC manufacturing process in real time if there is any sound change in the milling process. From the data report and the zero-crossing frequency (ZCR) difference in different amplitude ranges, it can be seen that aluminum has a higher zero crossing frequency than wood when cutting by CNC machine. Even the Mel spectrogram graph shows high sound density in the sound range of the CNC milling machine cutting aluminum. For safety monitoring, different types of data values indicate the safety level. If the data volume level is normal, it provides services accurately. Otherwise, the high and low values of the data difference indicate problems in the systems.

CRediT Author Statement

The authors confirm contribution to the paper as follows:

Conceptualization: Shafikul Islam Md, Subhra Prosun Paul, Jyoti Upadhyay, Syed Abdul Moeed, Reddy N V S M and Pompapathi M; **Methodology:** Subhra Prosun Paul and Jyoti Upadhyay; **Software:** Jyoti Upadhyay, Syed Abdul Moeed, Reddy N V S M and Pompapathi M; **Data Curation:** Shafikul Islam Md and Subhra Prosun Paul; **Writing- Original Draft Preparation:** Shafikul Islam Md, Subhra Prosun Paul, Jyoti Upadhyay, Syed Abdul Moeed, Reddy N V S M and Pompapathi M; **Investigation:** Shafikul Islam Md, Subhra Prosun Paul, Jyoti Upadhyay, Syed Abdul Moeed, Reddy N V S M and Pompapathi M; **Supervision:** Jyoti Upadhyay, Syed Abdul Moeed, Reddy N V S M and Pompapathi M; **Validation:** Subhra Prosun Paul and Jyoti Upadhyay; **Writing- Reviewing and Editing:** Shafikul Islam Md, Subhra

Prosun Paul, Jyoti Upadhyay, Syed Abdul Moeed, Reddy N V S M and Pompapathi M; All authors reviewed the results and approved the final version of the manuscript.

Data Availability
No data was used to support this study.

Conflicts of Interests
The author(s) declare(s) that they have no conflicts of interest.

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