Identification of noise source based on sound intensity in vertical CNC milling machine

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The paper presents a procedure for identifying the sound sources of a vertical CNC milling machine based on sound intensity measurements using the "two-microphone" method. Dominant noise sources for different operating modes in the machining process are determined based on contour maps of sound intensity levels measured on five sides of an imaginary parallelepiped that encompasses the machine. The research results can be used for designing noise protection systems for the dominant sound sources of the machine. The obtained results provide valuable guidance for designing machines that generate lower noise levels, which is crucial in machine certification processes.

Keywords: Identification of noise sources, sound intensity, CNC milling machine

1. INTRODUCTION

During the cutting process, the tool comes into contact with the material, resulting in the removal of a certain amount of material which leads to the occurrence of vibrations. Monitoring changes in sound intensity is crucial for determining the optimal parameters of the cutting process and achieving maximum productivity, as it enables us to predict potential machine component failures and identify errors in the production process. Furthermore, monitoring technology contributes to increased safety in manufacturing. Various studies have examined different monitoring techniques for the cutting process, dividing them into direct and indirect approaches [1,2,3].

Direct approach focuses on measuring the actual values of cutting process parameters. Although this method is highly accurate, it often requires interrupting the machining process and has strict environmental requirements. Therefore, it is primarily used in laboratory conditions and is not efficient for detecting real-time phenomena occurring during processing.

Using indirect methods, it is possible to determine cutting process parameters through the use of empirical correlations and analysis of measured signals. Despite having lower precision than the direct approach, it has the advantage of detecting errors early. Consequently, methods such as the analysis of load forces, electrical energy consumption, temperature, vibrations, and noise are frequently employed to predict the parameters associated with cutting processes. [1]

By using this method, it is possible to identify and monitor noise sources during machining, which is of great importance for effective noise management. Identifying noise sources holds significant importance in noise control processes. Currently, there are several methods for testing noise, including measuring sound pressure and sound intensity. Scalar measurements of sound pressure is highly susceptible to environmental factors. Additionally, using these methods it is difficult to determine the exact direction and location of the source of the sound. In order to measure sound pressure and determine sound power, specialized anechoic or reverberation chambers are often required, which can be expensive. [4]

It is possible to overcome these challenges using the method of sound intensity measurement. As sound intensity is measured as a vector, environmental influences are eliminated from measurement results. This method provides information about the level of sound intensity in the direction of sound propagation. Additionally, it allows for precise identification of the main source of noise and visualization of the distribution of sound intensity. Noise source identification is greatly enhanced by the use of sound intensity measurements, and the management of noise is more effective as a result. [5]

Identification of noise sources in the educational machine, the CNC 3-axis vertical milling machine UNI-FRAES3, manufactured by UNIMAT [6], holds significance from multiple aspects. In this study, we explore the process of noise source identification on the machine and emphasize its practical importance. The identification of noise sources accurately enables the proper maintenance of machines, the diagnosis of problems, the improvement of worker safety, and the optimization of designs Furthermore, noise source identification permits us to comply with standards regulating workplace noise. In the experimental part of the research, sound intensity measurements were conducted based on the ISO 9614-1 standard [7] during the milling process. The workpiece material was wood, and the tool used was a end mill with a diameter of d=1.6 mm, while the cutting parameters were a cutting depth of a=1 mm and a milling width of b=2 mm

2. THEORETICAL BACKGROUND

2.1. Sound Intensity

Sound intensity refers to the measurement of acoustic energy flow per unit area. Sound intensity is a vector quantity and its unit is W/m^2. Sound intensity is often converted to sound intensity level in decibels (dB), by dividing it by the reference intensity 1 pW/m^2 ($1x10^{-12}$). The active part of sound intensity, also known as the real part, represents the propagating component of the sound field. It refers to the actual energy being transmitted through the medium. On the other hand, the reactive part of sound intensity, or the imaginary part, represents the

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non-propagating component of the sound field. It refers to the energy that is stored or released by the sound field without being transmitted. [8]

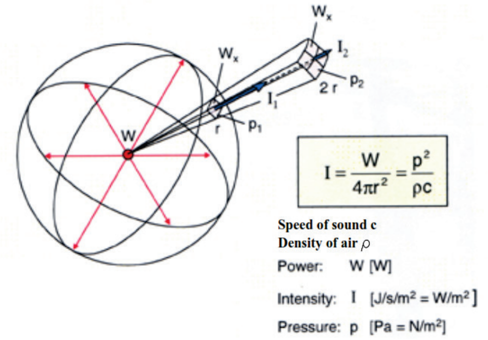

Figure 1: Definition of Sound Intensity [10]

It can be seen in figure 1 that the relationship between the three basic parameters of sound under free field conditions is illustrated by an omnidirectional sound source emitting a certain amount of power W. A surface intensity I on the surface at the distance r is the radiated sound power W divided by the surface area $4\pi r^2$. Alternatively, the intensity I at a distance r is equal to the sound pressure p squared divided by the impedance ρc of the air.

Sound fields are typically described using sound pressure, which is the quantity we perceive as the loudness of sound. However, sound fields are also fields of energy, where kinetic and potential energy are generated, transmitted, and dissipated. Sound intensity is a measure that defines the time-averaged rate of energy flow per unit area. A mathematically precise definition is that the sound intensity vector is equal to the time-averaged product of the instantaneous pressure and the corresponding particle velocity at the same position. [9]

$$\vec{I} = \overline{p(t)\cdot\vec{u}(t)} \quad (1)$$

Where p(t) is the instantaneous pressure, u(t) bis the particle velocity and the timeaveraging is indicated with a bar.

A sound intensity measurement based on Eq.1 is challenging. Currently, there are no appropriate transducers to directly measure particle vibration velocity. Consequently, indirect methods are used. In other words, it is a dual-microphone system, which is referred to as the p-p method.

2.2. "Two Microphones" Method for Noise Source Identification

Sound intensity is most commonly measured using an intensity probe. This method involves placing two microphones close together.

The advantage of using sound intensity measurement over sound pressure measurement to calculate the sound power of a source is that intensity is determined only for the direction formed by the two microphones of the intensity probe. This allows for spatial selection of the sound sources being analyzed and eliminates the influence of other sources that could potentially interfere with the analysis [5]. Measurements can be taken at several points or continuously to form a specific curve in space using the probe [8]. Measurements at discrete points are more commonly used in practice as they allow for a more convenient measurement procedure, with pauses possible between individual points. If measurements are taken at discrete points, a grid of points is formed where measurements are taken, typically a few centimeters away from the sound source.

A sound intensity probe consists of two microphones, and based on the measurements of the sound field at two closely spaced positions in space, the sound intensity can be estimated. Estimating sound intensity essentially involves estimating the phase of the sound field.

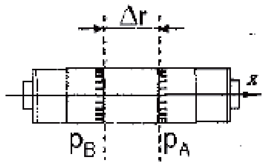

Figure 2: Face to face dual-microphone structure [4]

It's shown in Figure1 that A and B are two microphones, and Δr is the distance between them. here is a sound pressure grade between the dual microphones when the sound wave is transmitted. The particle velocity can be represented by Eq.2

$$u(t) = -\frac{1}{\rho_0}\int \frac{\partial p(t)}{\partial x}dt \quad (2)$$

When Δr is far smaller then wavelenght λ, $\frac{\partial p(t)}{\partial x}$ can be rewrite as $\frac{p_A(t) - p_B(t)}{\Delta r}$. The midpiont sound pressure of the dual-microphone can be seen as $p(t) = \frac{p_A(t) + p_B(t)}{2}$.

Accordingly, Eq.3 shows the sound intensity instantaneously in *x* direction. [4]

$$I(t) = p(t)\cdot u(t) = \frac{1}{2\rho_0 \Delta r}\left[p_A(t) + p_B(t)\right]\int\left[p_A(t) - p_B(t)\right]dt \quad (3)$$

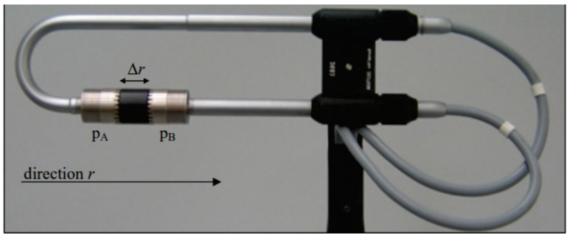

Figure 3: Sound intensity in one direction r is estimated with two closely spaced microphones

Using two microphones to estimate sound intensity has the advantages of being a common transducer in acoustics, being adaptable and being easily calibrated. Furthermore, the particle velocity and the sound pressure are calculated simultaneously at the same location.

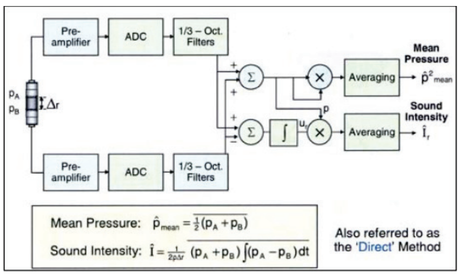

Figure 4: Estimation of Sound Intensity using Constant Percentage Bandwidth [10]

In order to estimate sound intensity, the microphone signals from the preamplifiers are converted from analogue to digital signals using a constant percentage bandwidth analyzer (see figure 4). A mean pressure is obtained by adding the outputs from the third-octave filters, squared, and averaging them.
Taking the sum and difference of the third-octave filters, we can calculate sound intensity. The difference is then integrated over time The difference is a quantity which is proportional to the particle velocity and the sum is a quantity, which is proportional to the pressure midway between the two microphones. Then the difference and the sum are multiplied and averaged.
Finally the scaling factor of $1/(2\rho\Delta r)$ generates the result, where ρ is the density of the air and Δr is the separation between the two microphones. This is called the direct method, because both intensity and mean pressure can be calculated directly according to the formulas. [10]

3. EXPERIMENT OF MILLING MACHINE NOISE SOURCE IDENTIFICATION

3.1. Classification of Milling Machine Noise

Among all the noise sources during the cutting process on vertical CNC milling machine, nearly all electrical and mechanical components of the machine can generate noise (power supply, electric or stepper motors, main and auxiliary motion systems, etc.) even during idle and rest periods. On the other hand, the tool and workpiece can generate noise only when the cutting process is underway. Static components, such as the supporting structure, can also generate noise due to mechanical excitation during the machining process. The main sources of noise on the milling machine are:

1. The drive motor of the milling machine is one of the main sources of noise. The operation of the motor can generate high-frequency sounds that are perceived as noise. The quality and efficiency of the motor can impact the level of noise it produces.

2. During the machining process, the tool (milling cutter) comes into contact with the workpiece material, resulting in vibrations that generate noise. The quality and sharpness of the cutting tool, as well as the type of material being machined, can impact the noise level.

3. The vertical CNC milling machine consists of moving parts such as the worktable, lead screws and roller bearings. These parts can produce noise during their movement, especially if they are improperly lubricated or damaged.

4. Vibrations transmitted through the machine structure can produce structural noise. If the machine is not properly installed and secured, and lacks vibration damping systems, these vibrations can be amplified and result in increased noise due to resonance effects.

3.2. Test Model Description

The size of the milling machine, as shown in the figure 5, is L×W×H (355mm × 330mm × 390mm). During the experiment, the spindle speed was kept constant at 4000 rpm.

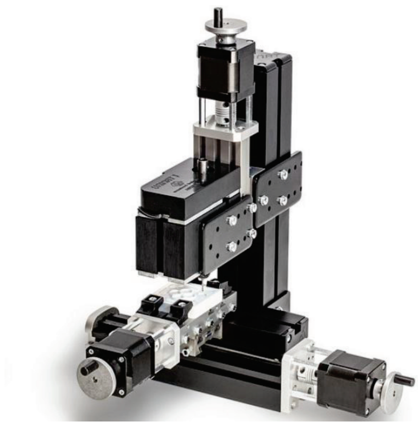

Figure 5: CNC 3-axis vertical milling machine UNI-FRAES3 [6]

3.3. Experiment Facility

The sound intensity testing system mainly consists of hardware and software components. The hardware system includes the B&K Type 2270, a two-channel sound level meter and analyzer, and components for the dual-microphone probe B&K 3654. The components for the dual-microphone probe consist of two B&K 4197 microphones with a diameter of 1/2 inch, a face-to-face probe configuration, and a spacing of 12 mm between the centers. The measurement signals are collected and processed using the B&K Type 2270 measurement analyzer. Post-processing of the measurement results can be done on a PC using the BK Connect measurement platform and Pulse Labshop software. This allows the creation of a contour plot of sound intensity level of the sound source. The main components of the measurement chain and equipment used in the experiment are shown in Figure 6 and Figure 7.

Figure 6 shows the B&K dual-microphone probe system. Figure 7 shows the B&K Type 2270 analysis system.

Figure 6. B&K dual-microphone probe system

Figure 7. B&K Type 2270 analysis system

3.4. Test Environment

Due to the limitations of the experimental conditions, the testing was conducted in a quiet and spacious room with all windows and doors open to reduce sound reflection and background noise. The temperature in the room was 20 degrees Celsius.

3.5. Measurement Points Disposition and Experiment Process

According to sound intensity measurement standards, the measurement surfaces should surround the machine tool as much as possible. [7] Figure 8 illustrates the orientation and data acquisition sequence of the measurement points. There are a total of 4x5 test fields on the front and back sides, 4x3 on the left and right sides, and 3x5 on the top side, resulting in a total of 79 experimental points covering all surfaces. Figure 7 shows the complete measurement grid of the machine and the arrangement of the grid on each measured surface. We use A-weighting during measurements as it best reflects the frequency response of the ear to sound intensity. During the experiment, the sound intensity measurement probe should be positioned perpendicular to the grid on the surface and be located at a distance of 0.5 meters from the emitting surface [7]. The sound intensity measurement probe is sequentially placed in a rectangular space to capture the central signal.

4. ANALYSIS OF EXPERIMENT RESULT

Figure 9 and Figure 10 show the measurement results of the sound intensity of a vertical three-axis CNC milling machine used for educational purposes. The presented results are obtained for a frequency range of 3 octaves. The frequency range consists of octaves: 1000 Hz, 2000 Hz, and 4000 Hz. This frequency range is chosen because it falls within the range of the intensity probe with the selected spacer and because it is the operational frequency range of the machine.

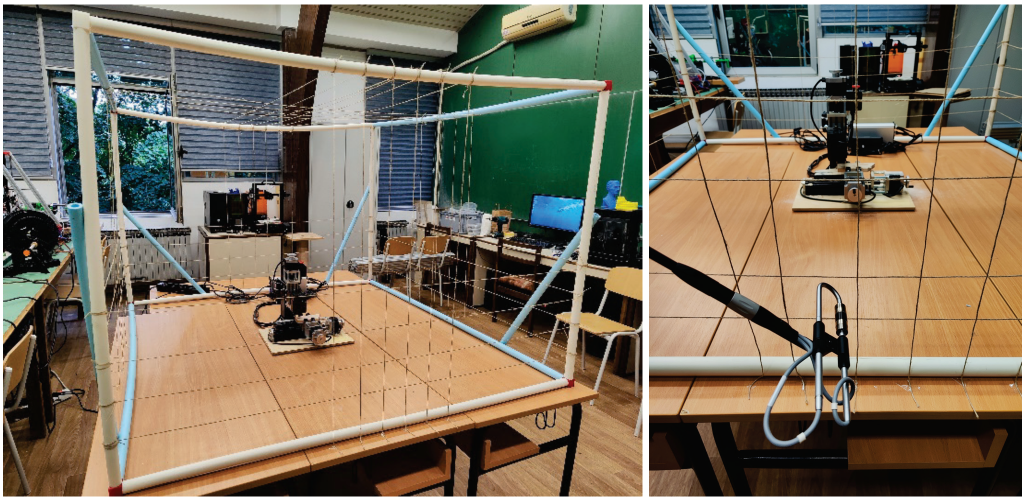

Figure 8: The measurement grid

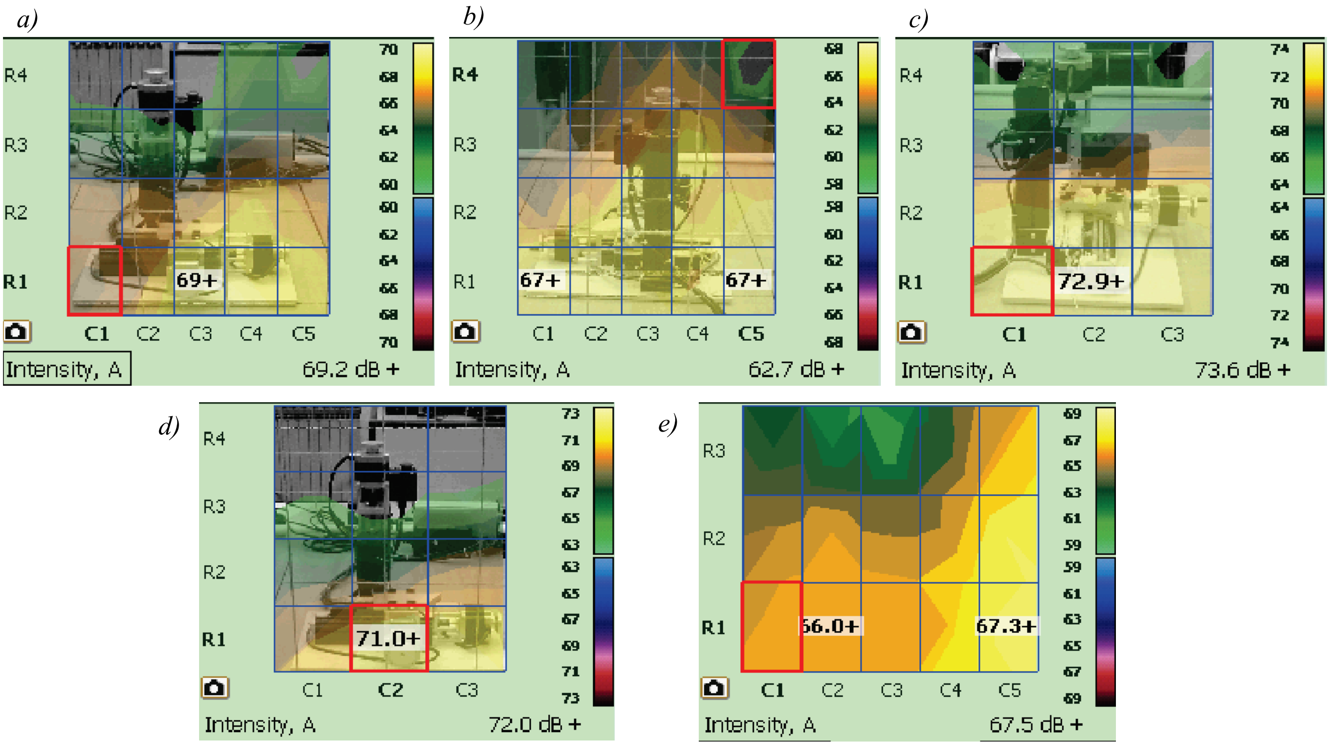

Figure 9: Sound intensity contour map on the: a) front, b) back, c) left, d) right and e) top surface

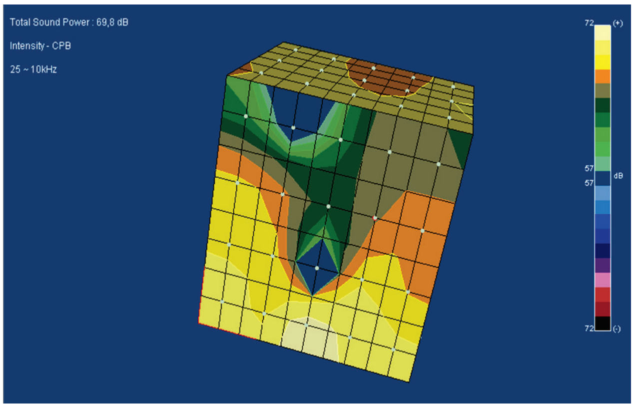

Figure 10: Equivalent sound intensity map

As can be seen from Figures 9 and 10 it seems that the milling machine's left and right sides have the highest sound intensity levels. It has been estimated that the maximum sound intensity on the right side is 71 dB(A) and on the left side it is 72.9 dB(A).

From the analysis of the entire equivalent sound intensity map, we can determine that the main noise source is the machine motor. Figure 12 shows that the sound intensity is highest on the left and right sides of the machine, with slightly higher values on the left side due to the motor bracket on the right side, which covers the entire surface of the motor.

Figure 11: The sound intensity value of every point on the a) front, b) back, c) left, d) right, and e) top surface

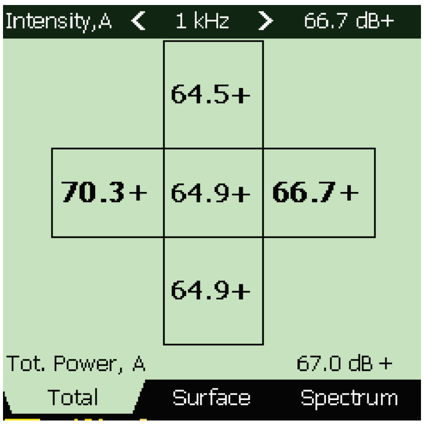

Figure 12: Total sound intensity on the measuring surfaces

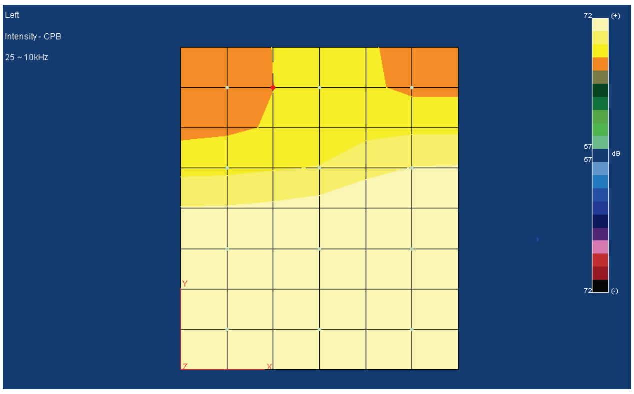

Figure 13: Sound intensity contour map on the left surface

5. CONCLUSION

In this study, the classification of noise from the CNC 3-axis vertical milling machine UNI-FRAES3 was performed, followed by the identification of noise sources on the machine surface based on sound intensity measurement method. Based on the noise map, it can be concluded that the main source of noise is the machine motor, particularly on the left surface.

The sound intensity method has a good ability to resist background noise. It has low requirements for test conditions and can be conveniently applied for noise testing and analysis of equipment. This enables us to effectively reduce the noise of experimental equipment by implementing appropriate measures. Additionally, sound intensity analysis technology can also be used to determine the sound power of sources. Sound power is more accurately determined through sound intensity rather than sound pressure, as it allows for a more precise calculation of the scalar product of the sound intensity vector and the corresponding vector of the elemental surface, with less demanding equipment and fewer restrictions in test conditions

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