Design of a Vibration Instrumentation Device Using an ADXL Accelerometer Sensor on an Arduino-Based Vertical Milling Machine

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Abstract.
The development of the manufacturing industry demands a machining process that has a high level of precision and reliability, so monitoring the condition of the machine is one of the important aspects to maintain the quality of the production process. This study aims to design and test an Arduino Mega 2560-based vibration instrumentation device using an accelerometer sensor ADXL345 to measure vibration in vertical milling machines. The developed system measures vibration acceleration on the X, Y, and Z axes, then calculates the Total Root Mean Square (RMS) value as an indicator of the machine's vibration level. The test was carried out 15 times on a vertical milling machine with the same machining parameters, then the measurement results were compared with the HT-1201 vibration meter as a reference tool. The test results showed that the Total RMS value obtained was in the range of 0.807–1.586 m/s². The validation process resulted in an average error value of 12.95%, and an average accuracy of 87.05%. The results show that the developed tool has a good level of conformity with standard measuring instruments so that it is suitable for use as an alternative to vibration monitoring in vertical milling machines.

Keywords: *ADXL345, Arduino Mega 2560, vibration instrumentation, vertical milling machine and RMS, tool validation.*

I. INTRODUCTION

The development of the manufacturing industry demands a production process that is able to produce components with a high level of precision, good surface quality, and optimal efficiency. One of the machining processes that is widely used to produce precision components is the vertical milling process because it has high flexibility in producing various geometric shapes of components [1]. In the milling process, cutting stability is an important factor that determines the quality of the final product, the life of the chisel, and the productivity of the machining process [2].

Vibration is one of the unavoidable phenomena in the milling process. Vibrations occur due to the interaction between the chisel, workpiece, spindle, and machine structure during the cutting process [2]. The periodically changing cutting force causes dynamic excitation which can increase the amplitude of the machine's vibration. These conditions become increasingly complex as cutting parameters such as spindle rotation, feeding motion, and feeding depth change [2],[3]. Excessive vibration can lead to a decrease in the surface quality of the workpiece, accelerate chisel wear, increase noise, and decrease the life of machine components [1],[4].

In industrial practice, the condition of engine vibration is often used as an indicator of engine health because it is able to provide information about the condition of mechanical components that are in operation [5]. The severity of vibration is generally evaluated based on the ISO 10816 standard which uses the Root Mean Square (RMS) parameter as an indicator of the vibration energy level in the machine [6]. A high RMS value indicates an increase in vibrational energy which can indicate imbalance, misalignment, bearing damage, and other mechanical malfunctions [2],[5],[6].

Vibration monitoring is an important part of the implementation of predictive maintenance because it is able to detect symptoms of damage at an early stage before more serious system failures occur [4],[5]. By monitoring vibration conditions regularly, maintenance actions can be planned more effectively so that they can reduce downtime, improve engine reliability, and reduce maintenance costs [4]. Therefore, an accurate and easy-to-use vibration monitoring system is an important need in both industrial and educational environments.

Vibration measurement is generally carried out using a vibration meter as a standard measuring tool. Despite having a good level of accuracy, the use of vibration meters still has some limitations, especially in terms of relatively high procurement costs and limitations in integration with microcontroller-based monitoring systems and real-time data acquisition [7]. This condition is a challenge in the development of a vibration monitoring system that is economical and easy to apply to educational laboratories and small-scale industries [7].

The development of digital sensor technology and microcontrollers opens up opportunities in the development of low-cost vibration instrumentation systems. Arduino is one of the most widely used microcontroller platforms because it has high flexibility, ease of programming, and relatively low implementation costs [8]. One of the most widely used sensors for vibration measurement is the ADXL345 accelerometer which is able to measure acceleration on three axes, namely the X, Y, and Z axes in real-time [8],[9]. This sensor works based on Micro Electro Mechanical System (MEMS) technology so that it is able to detect acceleration changes with fairly good sensitivity [9].

Several previous studies have developed vibration monitoring systems using accelerometer sensors and microcontrollers. Musyaffa [10] showed that an Arduino-based monitoring system is able to measure vibration in real-time on electric motors. Harto and Nurman [9] also reported that the use of accelerometers can be an alternative to vibration measurement at a relatively low cost. Research by Saputra et al. [11] shows that cutting parameters such as feed rate and depth of cut have an effect on the increase in vibration during the milling process. However, most of these studies still focus on monitoring systems or vibration analysis without validating measurement results against standard measuring instruments [9],[10],[11].

Based on the study, there is still a research gap related to the development of vibration instrumentation tools that are not only able to monitor in real-time but also have validated measurement results against standard measuring instruments. Therefore, this study aims to design and realize a vibration instrumentation tool using an Arduino Mega 2560-based ADXL345 accelerometer sensor on a vertical milling machine and validate the measurement results of the HT-1201 vibration meter. The vibration data obtained was processed using the Root Mean Square (RMS) method and compared with the measurement results of standard tools to determine the error rate and accuracy of the developed system. Thus, this research is expected to produce a vibration monitoring system that is economical, practical, and has a good level of reliability to support educational activities and small-scale industries.

II. METHODS

This study uses a quantitative experiment method with a *design and build* approach to develop vibration instrumentation tools based on ADXL345 accelerometer sensors and Arduino Mega 2560 on vertical milling machines. The research stages include literature study, system design, tool manufacturing, testing, validation, and analysis of measurement data. The literature study was conducted by examining various references related to engine vibration theory, vertical milling process, ADXL345 accelerometer sensor, Arduino Mega 2560, *Root Mean Square* (RMS) method, and ISO 10816 standard as a reference for evaluating engine vibration conditions. In addition, previous research on microcontroller-based vibration monitoring systems was used as a basis for the development of the designed tool.

The vibration instrumentation system consists of an accelerometer sensor ADXL345 as a vibration detector, an Arduino Mega 2560 as a data processing unit, and a 16×2 LCD as the display medium for the measurement results. The sensor is ADXL345 used to measure vibration acceleration on three axes, namely the X, Y, and Z axes. The acceleration data obtained by the sensor is sent to Arduino via I2C communication to be processed into RMS values, then displayed in real-time on the LCD. The test was carried out on a turret-type vertical milling machine using S50C steel material and a 10 mm diameter HSS End Mill chisel. The sensor ADXL345 mounted on the workpiece clamping blade to represent the vibrations that occur during the machining process. Data collection was carried out under fixed cutting conditions with a spindle rotation of 1100 rpm, *a feed rate* of 23 mm/min, and a feeding depth of 1.5 mm. The test was carried out 15 times to obtain representative data.

The vibration data obtained from the sensor ADXL345 processed using *the Root Mean Square* (RMS) method. The RMS value is calculated on each of the measurement axes, namely the X, Y, and Z axes. Furthermore, the Total RMS value is obtained from the combination of the three axes using the resultan vector method and is used as the main parameter to represent the vibration level of the machine during the machining process. To determine the level of reliability of the developed tool, validation was carried out by comparing the measurement results of the ADXL345 sensor against the HT-1201 vibration meter as a standard measuring tool. Both devices take measurements at the same operating conditions so that the results obtained can be compared directly. The performance of the tool is evaluated through the calculation of error value and accuracy based on the measurement results of the two tools. The validation results are used to determine the feasibility of the vibration instrumentation system developed on vertical milling machines.
Equations used
The RMS value is calculated using Equation (1).

$$X_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2} \qquad \text{…………………(1)}$$

Description:
RMS = nilai *Root Mean Square* (m/s²)
xi = the data of the i acceleration (m/s²)
n= amount of measurement data
The overall RMS value is calculated using Equation (2)

$$RMS_{\text{Overall}} = \sqrt{RMS_X^2 + RMS_Y^2 + RMS_Z^2} \qquad \text{……………………(2)}$$

Description:
RMSoverall= overall RMS (m/s²)
RMSx= X-axis RMS value (m/s²)
RMSy= Y-axis RMS value (m/s²)
RMSz= Z-axis RMS value (m/s²)
The error value is calculated using Equation (3).

$$Error(\%) = \left|\frac{S - VM}{VM}\right| \times 100\% \qquad \text{........................(3)}$$

Description:
S = the measurement result of the sensor ADXL345
VM=Vibration meter measurement results
Error(%)= percentage of measurement error
The accuracy value is calculated using Equation (4).

$$Accuracy(\%) = 100 - Error(\%) \qquad \text{..........................(4)}$$

Description:
Accuracy = Accuracy level of the tool (%)
Error = percentage of measurement error (%)

III. RESULT AND DISCUSSION

Vibration Instrumentation System

The developed vibration instrumentation system consists of an accelerometer ADXL345 sensor, Arduino Mega 2560, 16×2 LCD, and system power source. The sensor ADXL345 used to measure vibration acceleration on the X, Y, and Z axes in real-time. The measurement data is processed by the Arduino Mega 2560 to obtain the Root Mean Square (RMS) value and displayed on the LCD. The sensor is mounted on the workpiece clamping vise to represent the vibrations that occur during the milling process.

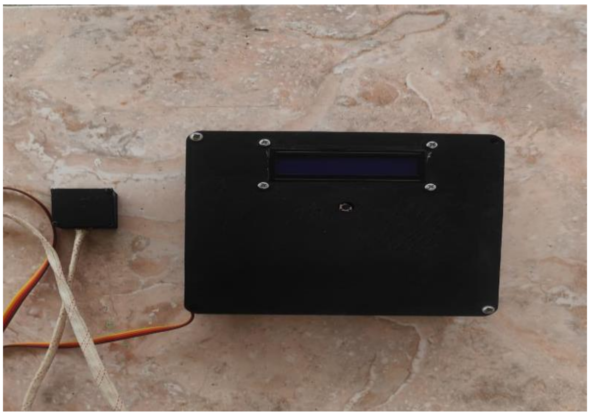

Fig. 1. ADXL345- and Arduino Mega 2560-Based Vibration Instrumentation System

Vibration Measurement Results

The test was carried out 15 times under the same cutting conditions, namely a spindle rotation of 1100 rpm, a feed rate of 23 mm/min, and a feeding depth of 1.5 mm. The results of sensor data processing ADXL345 shown in Table 2.

Table 1. RMS Measurement Results of ADXL345 Sensor

No	Measurement	Acceleration RMS X (m/s²)	Acceleration RMS Y (m/s²)	Acceleration RMS Z (m/s²)	Acceleration RMS Total (m/s²)
1	Data 1	1,135	0,494	0,168	1,249
2	Data 2	0,181	0,948	0,067	0,967
3	Data 3	0,231	0,762	0,130	0,807
4	Data 4	0,678	0,931	0,085	1,155
5	Data 5	0,114	0,879	0,043	0,887
6	Data 6	0,619	0,970	0,189	1,166
7	Data 7	0,587	1,416	0,268	1,555
8	Data 8	0,629	1,005	0,343	1,235
9	Data 9	0,987	0,599	0,543	1,276
10	Data 10	0,361	0,766	0,336	0,911
11	Data 11	0,684	0,796	0,121	1,056
12	Data 12	0,799	1,276	0,501	1,586
13	Data 13	0,616	1,077	0,187	1,255
14	Data 14	0,606	1,077	0,187	1,250
15	Data 15	0,607	1,115	0,685	1,443

Based on Table 2, the Total RMS value obtained is in the range of 0.807 m/s² to 1.586 m/s². The highest Total RMS value was obtained in the 12th test of 1,586 m/s², while the lowest value was obtained in the 3rd test of 0.807 m/s². These results show that the sensor is ADXL345 able to detect vibration changes that occur during the machining process.

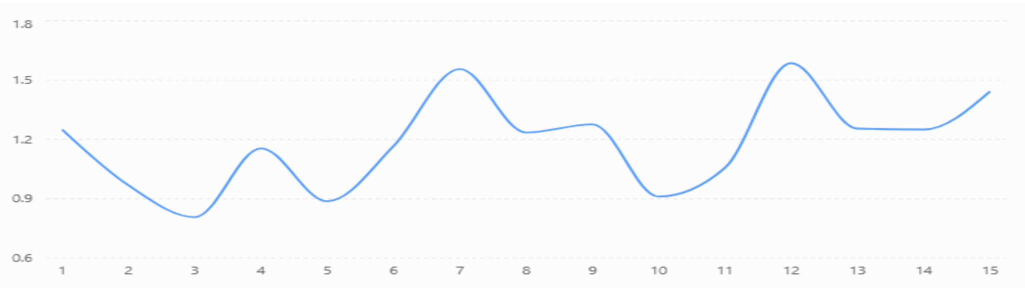

Fig. 3. RMS Total Measurement Results

Based on Table 2, the Total RMS value is in the range of 0.807–1.586 m/s². The highest score was obtained on the 12th test, while the lowest score was obtained on the 3rd test. These results show that the sensor is ADXL345 able to detect changes in vibration levels during the machining process. The Total RMS parameters obtained from the combination of the three axes were used as a representation of the overall condition of the engine vibration, in accordance with the data processing method used in this study.

Validation Results

Validation was carried out by comparing the RMS measurement results of the Total ADXL345 sensor against the HT-1201 vibration meter as a standard measuring tool. The results of the comparison of the two tools are shown in Table 3.

Table 2. Comparison of ADXL345 and Vibration Meter Measurements

Data	Vibration Meter (m/s²)	ADXL345 RMS Total (m/s²)
1	1.0607	1.250
2	1.0334	0.968
3	1.0005	0.807
4	1.0330	1.155
5	1.0904	0.887
6	1.0320	1.166
7	1.3715	1.556
8	1.2946	1.235
9	1.2394	1.276
10	1.2446	0.911
11	1.2361	1.056
12	1.2996	1.586
13	1.2977	1.255
14	1.2919	1.250
15	1.3092	1.443

Based on the measurement results, the Total RMS value obtained from the sensor ADXL345 has the same tendency as the measurement results of the HT-1201 vibration meter. This shows that the instrumentation system developed is able to represent the vibration conditions of the vertical milling machine quite well.

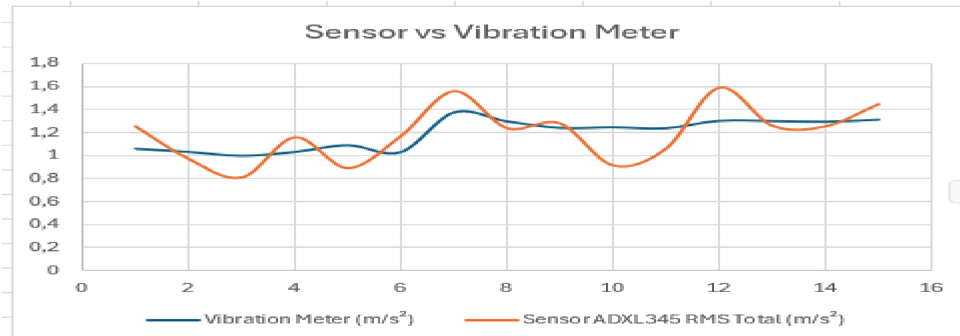

Fig. 4. Comparison Graph of ADXL345 and Vibration Meter Measurements

Based on Figure 4, the results of the RMS Total measurements using ADXL345 sensors show a trend that is in line with the measurement results of the HT-1201 vibration meter at all test points. Although there are some differences in values in each measurement, the pattern of vibration changes shown by the two tools is relatively similar. This shows that the sensor is ADXL345 able to follow the changes in vibration levels that occur during the machining process on a vertical milling machine.

The difference in measurement between the two devices is influenced by several factors, such as the sensitivity characteristics of the ADXL345 sensor, the position of the sensor installation on the beam, the transmission of vibration through the machine structure, and the presence of signal interference (*noise*) during the data acquisition process. However, the validation results show that the developed tool has a good level of compatibility with the HT-1201 vibration meter, so that it can be used as an alternative to an Arduino-based machine vibration monitoring system at a more economical cost.

Error and Accuracy Analysis

The performance of the tool was evaluated using error and accuracy parameters based on the validation results of the HT-1201 vibration meter.

Table 4. Error Results

No	Measurement	Error (%)
1	Data 1	17,85
2	Data 2	6,33

No	Measurement	Error (%)
3	Data 3	19,34
4	Data 4	11,81
5	Data 5	18,65
6	Data 6	12,98
7	Data 7	13,45
8	Data 8	4,68
9	Data 9	2,95
10	Data 10	26,80
11	Data 11	14,57
12	Data 12	22,04
13	Data 13	3,29
14	Data 14	3,24
15	Data 15	10,22
Average	**-**	**12,95**

The error value ranged from 2.95% to 26.80%, with an average value of 12.95%. The variation in error values is influenced by the sensitivity of the sensor, the position of the sensor installation on the ragum, signal interference during data acquisition, and the difference in measurement characteristics between the ADXL345 sensor and the vibration meter.

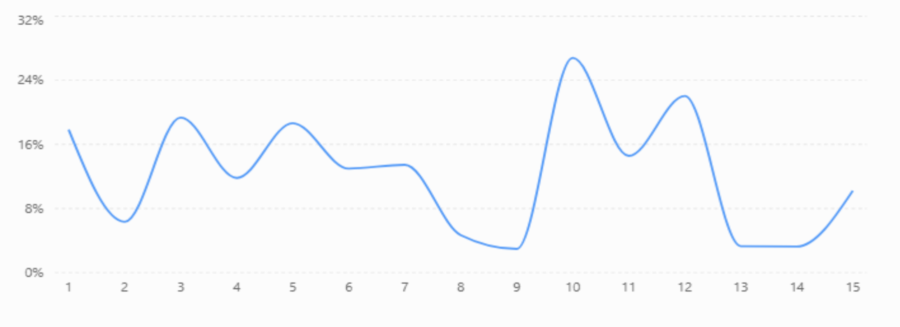

Fig. 5. Error Graph

Figure 5 shows the error percentage *of* the measurement results of the ADXL345 sensor against the HT-1201 vibration meter in 15 tests. The *error* value is in the range of 2.95% to 26.80% with an average value of 12.95%. The difference in *error values* in each test is influenced by the vibration conditions of the machine, the characteristics of the sensors, and the data acquisition process. Overall, *the error* value obtained indicates that the developed tool has an acceptable level of deviation from the standard measuring tool.

Next, the accuracy value of the tool is calculated based on the results of the errors obtained.

Table 5. Accuracy Results

No	Measurement	Accuracy (%)
1	Data 1	82,15
2	Data 2	93,67
3	Data 3	80,66
4	Data 4	88,19
5	Data 5	81,35
6	Data 6	87,02
7	Data 7	86,55
8	Data 8	95,32
9	Data 9	97,05
10	Data 10	73,20
11	Data 11	85,43
12	Data 12	77,96
13	Data 13	96,71
14	Data 14	96,76
15	Data 15	89,78
Average	**-**	**87,05**

Based on Table 5, an average accuracy value of 87.05% was obtained, with the highest accuracy of 97.05% in the 9th test and the lowest accuracy of 73.20% in the 10th test. This value shows that the tool is able to produce data that is close to the results of vibration meter measurements so that it is suitable for use as a vibration monitoring system.

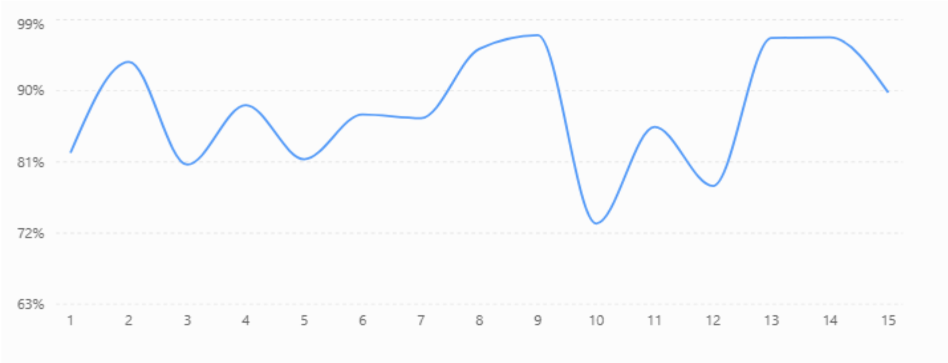

Fig. 6. Accuracy Graph

Figure 6 shows the accuracy level of the ADXL345 sensor-based vibration instrumentation tool at 15 tests. The accuracy value ranges from 73.20% to 97.05%, with an average of 87.05%. The results show that most tests produce an accuracy above 80%, so the designed tool has a good degree of compatibility with the HT-1201 vibration meter. Thus, the developed system is feasible for vibration measurement in vertical milling machines.

IV. CONCLUSION

Based on the results of the study, the Arduino-based vibration instrumentation tool uses an accelerometer sensor ADXL345 was successfully designed and implemented to measure vibration in vertical milling machines. The developed system is capable of measuring vibration on three axes (X, Y, and Z) as well as calculating the Total RMS value as a representation of the machine's vibration level during the testing process.

The test results show that the tool can work well in recording changes in vibration levels on vertical milling machines. Based on 15 tests, the total RMS value obtained was in the range of 0.807–1.586 m/s^2, indicating that the system was able to measure vibration variations consistently. The validation results of the HT-1201 vibration meter showed that the developed tool had good measurement performance with an average *error* value of 12.95%, an average accuracy of 87.05%, and an RMSE of 0.171 m/s^2. The results show that the tool has a good level of compatibility with standard measuring instruments, so it can be used as an economical and practical alternative to vibration monitoring in vertical milling machines.

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