Enhancing the Piezoelectric Accelerometer for Effective Monitoring and Diagnosis of Engineering Structures

Zine GHEMARI *
Mohamed Boudiaf University of M'sila, Algeria, ghemari-zine@live.fr, zine.ghemari@univ-msila.dz

Salah BELKHIRI
Mohamed Boudiaf University of M'sila, Algeria, salah.belkhiri@univ-msila.dz

Mohamed Razi MORAKCHI
Mohamed Boudiaf University of M'sila, Algeria, razi.morakchi@univ-msila.dz

Salah SAAD
Badji Mokhtar University of Annaba, Algeria, salahsaad2006@yahoo.fr

* Author to whom correspondence should be addressed

Abstract: - Vibrational analysis plays a pivotal role in predictive maintenance and condition-monitoring, providing the capability to identify emerging issues before they escalate into equipment failures, unplanned downtime, or safety hazards. Attaining maximum accuracy in vibrational measurements is crucial for the efficacy of these analyses. In this study, our objective is to enhance the measurement accuracy of the piezoelectric accelerometer, a fundamental transducer in vibrational analysis. We propose a novel formula that establishes a connection between the measurement accuracy of the sensor and the displacements of vibrational movements. This improvement is designed to elevate the precision of vibration analysis, reducing errors in fault detection and optimizing the outcomes of condition-based preventative maintenance initiatives. The overarching goal is to enhance the reliability of vibration analysis techniques, ensuring a more robust and efficient approach to machine condition monitoring and maintenance planning.

Keywords: - Accelerometer, Maintenance, Piezoelectric, Predictive.

1. INTRODUCTION

In the contemporary business landscape, enterprises must prioritize optimizing their machinery efficiency. This proactive approach ensures that machines operate at peak performance levels, resulting in heightened productivity and substantial cost savings. Beyond economic considerations, the impact of machinery efficiency on the environment is noteworthy. Operating machines more efficiently enables businesses to reduce their carbon footprint, contributing to environmental conservation [1-7].

The maintenance of engineering structures plays a pivotal role in ensuring their seamless functionality. This maintenance encompasses a spectrum of activities, including inspecting, diagnosing, and repairing machinery and electrical equipment. It involves meticulous examination and potential replacement of worn or defective parts, as well as the installation and adjustment of new components. The process of electrical machinery maintenance is not merely a routine procedure; it stands as a critical safeguard for the safety and reliability of electrical and maintenance systems. Furthermore, it serves as a preventive measure, averting unnecessary damage and mitigating the risk of breakdowns. Therefore, the holistic consideration of machinery efficiency and its maintenance extends beyond immediate operational benefits to encompass environmental sustainability, safety, and the longevity of vital systems [8-9].

One way to enhance machinery efficiency is through optimized piezoelectric accelerometer measurements. Piezoelectric accelerometers measure vibrations in engineering structures, providing insight into a system's health and helping to identify any potential issues before they become serious. By optimizing these measurements with advanced algorithms, businesses can maximize the performance of their machines and ensure optimal efficiency. This can result in improved productivity and cost savings for companies that invest in this technology. Another benefit of optimized piezoelectric accelerometer measurements is that they provide an early warning system for potential problems. By detecting abnormal vibrations in machinery quickly and accurately, companies can take action to prevent further damage or costly repairs down the line. This technology also allows preventive maintenance to be scheduled more effectively and efficiently, ensuring that machines are running optimally all the time [10-11].

Piezoelectric sensors are a high-tech solution for modeling physical behavior. These sensors use the piezoelectric effect to measure the forces and movements of objects in real-time. Making them ideal for applications in robotics, automotive, industrial, medical, and consumer products [12].

The piezoelectric effect is the ability of certain materials to produce an electrical charge when subjected to mechanical stress. This phenomenon has been known since 1880, but it wasn't until recently that its potential as a sensor technology was realized. Piezoelectric sensors are used in a variety of industries today and are becoming increasingly popular due to their accuracy and cost-effectiveness [13-15].

Unlike traditional sensors which rely on analog signals, piezoelectric sensors generate digital signals. This makes them more reliable and accurate as analog sensors can be prone to interference from external sources. Additionally, piezoelectric sensors are highly sensitive and capable of detecting even the slightest changes in force or movement. This makes them suitable for applications where accuracy is of utmost importance such as medical instruments or robotics [16].

Furthermore, piezoelectric sensors are easy to install and require minimal maintenance. They also have low power consumption compared to other types of sensors, making them an attractive option for long-term projects or applications with limited power supplies [17].

In this paper, the proposed approach employs a mathematical model of the accelerometer to forecast the device's output based on a given input. This model forms the foundation for an optimization algorithm designed to attain the desired performance. Through a combination of experiments and simulations, we validate the efficacy of our approach. The developed model and optimization algorithm offers valuable applications in optimizing accelerometer performance across various sectors, including automotive, aerospace, and industrial vibration monitoring.

Our methodology proves instrumental in enhancing the accuracy and reliability of vibration measurements, while concurrently mitigating costs associated with accelerometer maintenance and repairs. Moreover, the proposed model and algorithm serve as valuable tools for the advancement of new accelerometers, fostering improved performance. Beyond this, our approach serves as a valuable resource for designing sophisticated vibration analysis systems.

Our proposed model and optimization algorithm offer an efficient and cost-effective means of enhancing the performance of piezoelectric accelerometers and vibration analysis systems. The versatility of our method extends to other types of accelerometers, including MEMS accelerometers, making it applicable to the optimization of various vibration analysis systems.

2. IMPORTANCE OF PREDICTIVE MAINTENANCE

Predictive maintenance is a process of actively monitoring the condition of equipment. It uses advanced data analytics to identify potential problems before they cause a system failure. This means that preventive and corrective action can be taken to avoid costly repairs or equipment replacement. It also allows for better utilization of resources, as well as improved reliability and safety. The process of predictive maintenance relies on the use of vibration analysis tools. Vibration analysis is a form of non-destructive testing that measures the frequency, amplitude, and intensity of mechanical vibrations produced by machinery. By analyzing these vibrations, it is possible to detect anomalies in machine operation that could indicate an impending problem. Using vibration analysis, technicians can identify specific issues with machinery before they become serious enough to cause a breakdown or damage to the equipment. This can save time and money by allowing for quick repair or replacement before it becomes necessary. Additionally, vibration analysis can be used as part of a proactive approach to preventative maintenance. This allows for more efficient maintenance scheduling and greater control over operational costs. Overall, predictive maintenance through vibration analysis provides companies with an effective way to reduce operational costs while improving reliability and safety. By proactively monitoring machines and detecting potential problems early on, companies can save time and money while ensuring the continued performance of their equipment [18-20].

3. VIBRATION ANALYSIS

The necessity of measuring vibrations stems from several critical factors. Initially, vibrations serve as sensitive indicators of machine operational conditions. Variations in amplitudes and frequencies can signal imbalances, bearing defects, mechanical play, or other mechanical issues (see Figure 1). Continuous monitoring of these vibration parameters enables the early identification of signs of degradation, facilitating corrective actions before major failures occur [21].

Figure 1. Vibration analysis

Furthermore, vibration measurement plays an important role in predictive maintenance. Unlike fixed schedules, predictive maintenance utilizes real-time vibration data to strategically plan maintenance activities as required. This approach not only reduces maintenance costs but also minimizes unplanned downtime, thereby enhancing overall operational efficiency [22].

In the realm of civil structures, such as bridges and buildings, vibration measurement offers valuable insights into structural integrity. It enables the identification of excessive movements, abnormal deformations, and warning signs of failure, contributing significantly to infrastructure safety and public protection [23].

Accurately estimating frequencies in the signal domain is often challenging due to factors such as noise, interference, temporal resolution limitations, and other complexities. Precision in frequency estimation is essential for a wide range of applications, including signal processing, communications, and monitoring [24].

While the Fast Fourier Transform (FFT) is a powerful technique for frequency analysis, it may have limitations, particularly when dealing with short signals or those containing impulse components. To address this concern, a frequency evaluation method is introduced that considers structural responses to swept sinusoidal excitations in both increasing and decreasing sweep directions. The efficacy of this method in accurately extracting natural frequencies is thoroughly evaluated [25].

By utilizing vibration analysis techniques, engineers and technicians can quickly identify potential problems and take corrective action before the system fails. Additionally, vibration analysis can help detect issues early allowing companies to take proactive steps to maintain their systems. An added benefit of vibration analysis is its applicability to both new and existing systems, facilitating long-term maintenance and quality improvement. With the right vibration analysis strategy, companies can ensure their systems operate at peak performance, reduce maintenance costs, and increase their bottom line [26-28].

By accurately measuring these vibrations, we can gain insights into the workings of everything from machinery to the human body. Improved measurement accuracy in vibrational analysis offers several important benefits. First, it helps us to better understand complex systems. Second, it allows us to design more effective solutions to problems. Third, it helps us to avoid potential hazards. For these reasons, it is clear that improved measurement accuracy in vibrational analysis is essential. Continued investment in research and development in this area is crucial to fully realizing the benefits of this technology [29-30].

4. MATHEMATICAL MODEL OF THE PHYSICAL BEHAVIOR OF THE SENSOR

A damper-spring mass system represents a mechanical configuration with intricate dynamic characteristics. Comprising three primary components – a mass, a damper, and a spring (refer to Figure 2) – this system exhibits nuanced behavior. The spring exerts a restorative force on the mass, while the damper acts to dampen the motion of the mass. The dynamics of a damper-spring mass system are influenced by various factors, including the attributes of external forces, the spring's stiffness, and the damping coefficient of the damper. Under specific conditions, the system may demonstrate chaotic or periodic behavior. Predicting the precise future states of the system is challenging due to its inherent complexity. Nevertheless, the intricate nature of damper-spring mass systems renders them valuable for exploring diverse phenomena in physics and engineering.

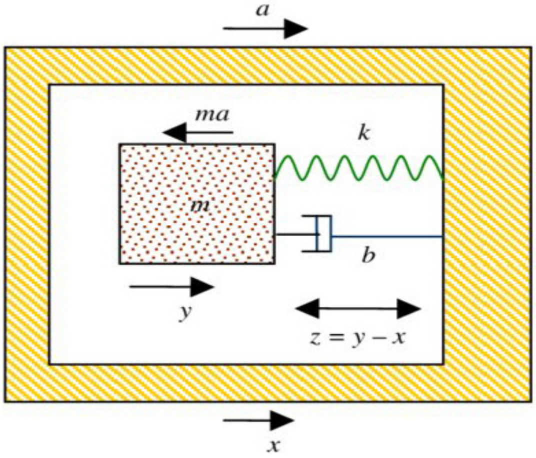

Figure 2. Piezoelectric sensor [24]

A damper-spring mass system is a type of mechanical system that can model the behavior of objects under various conditions. The system consists of a mass (m), a spring (k), and a damper (c). The spring and damper are connected in series, while the mass is connected to both the spring and damper in parallel. This system can model the behavior of objects under conditions, such as vibration, shock, and impact [31-35].

The piezoelectric sensor captures the relative movement z(t) which is expressed by the following relationship:

$$\mathrm{z(t)}\ = \mathrm{x(t)} - \mathrm{y(t)} \tag{1}$$

Applying Newton's law of motion, we get:

$$\sum \mathrm{F} = \ \mathrm{m}\gamma = m(\frac{d^2z}{dt^2}) \tag{2}$$

The motion of the mass-spring-damper system can be expressed by the following equation:

$$m\left(\frac{d^2z}{dt^2}\right) + c\left(\frac{d^2z}{dt^2}\right) + kz(t) = -m\left(\frac{d^2y}{dt^2}\right) \tag{3}$$

m: mass, c: friction coefficient, k: elasticity coefficient, y: absolute motion, and (d^2y/dt^2) : absolute acceleration.

By replacing (d/dt) with Laplace's coefficient (s), we can write Eq.3 as follows:

$$ms^2z + csz + kz\ = -ms^2 \tag{4}$$

The sensor’s natural frequency is expressed by:

$$\omega_0 = \sqrt{\frac{k}{m}} \tag{5}$$

The damping rate of the sensor is as follows:

$$\xi = \frac{c}{2m\omega_0} \tag{6}$$

ω_0 is the natural frequency, ω is the frequency of the vibratory motion and ξ is the damping rate.

By replacing Eq.5 and Eq. 6; we find:

$$z = \frac{-ys^2}{s^2+2\xi\omega_0 s+{\omega_0}^2} \tag{7}$$

We obtain the following equation by substituting Laplace's coefficient (s) by (jω):

$$z = \frac{\omega^2 y}{-\omega^2+2j\xi\omega\omega_0+{\omega_0}^2} \tag{8}$$

By multiplying the denominator of equation (8) by ω_0^2/ω_0^2, equation (9) is obtained:

$$z = \frac{\omega^2 y}{{\omega_0}^2[1-(\omega/\ \omega_0)^2+2j\xi\omega/\omega_0]} \tag{9}$$

Equation (9) is a complex function; its module is extracted as follows:

$$z = \frac{\omega^2 y}{{\omega_0}^2[(1-(\omega/\ \omega_0)^2)^2+(2\xi\omega/\omega_0)^2]^{1/2}} \tag{10}$$

By multiplication of the equation (10) by ω_0^2:

$${\omega_0}^2 z = \frac{\omega^2 y}{[(1-(\omega/\ \omega_0)^2)^2+(2\xi\omega/\omega_0)^2]^{1/2}} \tag{11}$$

Eq.11 allows us to write the absolute acceleration as follows:

$$\frac{d^2y}{dt^2} = \omega^2 y \tag{12}$$

The relative acceleration is expressed by:

$$\frac{d^2z}{dt^2} = {\omega_0}^2 z \tag{13}$$

The use of the condition $\omega/\omega_0\ <<\ 1$ to choose the suitable sensor for the frequency range of the vibratory movements allows to optimize the measurement precision, therefore Eq.10 is written as follows:

$${\omega_0}^2 z\ \ \approx\ \ \omega^2 y \tag{14}$$

So:

$$\frac{d^2z}{dt^2} \approx \frac{d^2y}{dt^2} \tag{15}$$

The ratio between absolute acceleration and relative acceleration is the measurement accuracy of the sensor which is given by:

$$\mathrm{P} = \left(\frac{\frac{d^2z}{dt^2}}{\frac{d^2y}{dt^2}}\right) = ({\omega_0}^2 z)\ /(\omega^2 y) \tag{16}$$

P: accuracy of the piezoelectric accelerometer

By the use of Eq.12, the accuracy relation becomes as follows:

$$\mathrm{P} = \frac{1}{[(1-(\omega/\ \omega_0)^2)^2+(2\xi\omega/\omega_0)^2]^{1/2}} \tag{17}$$

We use Eq.10 to extract the new expression of displacement as a function of the accuracy which is shown by:

$$z = \omega^2 y\ \mathrm{P}/{\omega_0}^2 \tag{18}$$

The use of this approach can help to guide the design and development of new piezoelectric accelerometers. This design principle should focus on producing an accelerometer with the highest possible performance, measured by factors such as low noise, low power consumption, high sensitivity, and fast response time.

Designers should consider factors such as the size and shape of the piezoelectric element, the type of material used, the number of elements, the design of the electrodes, the measurement range, the frequency response, and the type of signal conditioning used. All of these factors should be carefully evaluated and optimized for the best performance. Additionally, new technologies such as microelectromechanical systems (MEMS) should be explored to determine if they can improve the design.

The use of this expression also requires designers to consider cost when designing the accelerometer. By understanding the trade-offs between performance and cost, designers can develop an accelerometer with the best possible performance at the lowest possible cost. Ultimately, the use of this expression should help create a piezoelectric accelerometer that achieves the highest possible performance at a reasonable cost.

5. CHOICE OF THE PIEZOELECTRIC SENSOR PARAMETERS

Vibrational analysis is an important part of engineering and industrial processes, employed for detecting, diagnosing, and preventing mechanical faults, while also enhancing product efficiency and quality. Ensuring accurate analysis results necessitates improving the measurement accuracy of the equipment used. There are several benefits to improving the accuracy of measurements in vibrational analysis. Firstly, increased accuracy leads to better diagnosis of mechanical faults and more accurate maintenance decisions. This can help reduce downtime and save money by preventing costly repairs or unnecessary replacement parts. Secondly, improved accuracy can improve product performance and quality by allowing engineers to identify problems before they escalate into serious issues. Finally, accurate data can be used for predictive maintenance tasks, allowing engineers to anticipate when maintenance should be performed before any damage occurs.

The performance of the piezoelectric sensor can be improved by adjusting the electrical and mechanical parameters such as the piezoelectric material, pre-stress, geometry, and boundary conditions of the sensor. Additionally, the optimization of these parameters can be achieved through computer simulation and optimization techniques. These techniques can help to optimize sensor parameters such as natural frequency and damping ratio, which are key for enhancing the performance of the piezoelectric sensor. Furthermore, selecting the appropriate piezoelectric material and other input parameters can improve the performance of the sensor. Proper packaging and mounting of the piezoelectric sensor can also improve its performance.

The damping rate of a piezoelectric accelerometer affects its frequency response and dynamic range. Typically, increasing the damping rate choice improves the accelerometer's frequency range, reduces noise levels, and increases sensitivity. However, an excessively high damping rate can raise the mechanical resonance frequency, potentially reducing the device's frequency response. Therefore, selecting the optimal damping rate for a piezoelectric accelerometer involves balancing the desired frequency response and dynamic range carefully.

Using the optimal damping rate for a piezoelectric accelerometer can improve the accuracy of vibration analysis and the overall performance of the device. It can also reduce maintenance costs and extend the device's lifespan, making it a cost-effective tool for vibration analysis and condition-based preventive maintenance.

The damping rate is selected by simulating equation (17) across various damping rate values. The simulation is executed, and the results are recorded in Table 1. The damping rate that yields the most desirable results is then chosen. The simulation parameters are outlined in Table 1:

Table 1. Simulation parameters

Parameters	Values
ω_0 (Hz)	2400
y (mm)	0.3
ζ	0.63, 0.64, 0.65, 0.66, 0.67, 0.68, 0.69, 0.7, 0.71, 0.72
ω(Hz)	0 to 1000

The simulation results of equation (17) are summarized in the following figure (Fig.3):

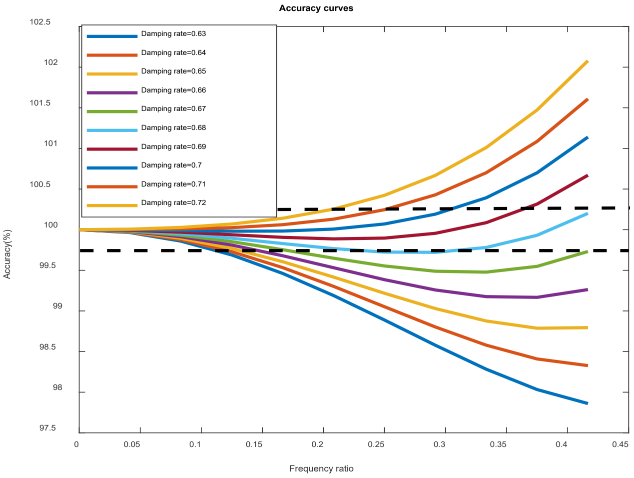

Figure 3. Simulation results of equation (17) for ten values of the damping rate

Figure 3 illustrates the accuracy according to the frequency ratio for ten damping rate values. As shown in Figure 3, the damping rate value which limits the precision to a value of 99.8% is between 0.68 and 0.69. To choose the most accurate value of the damping rate, equation (17) is simulated for the three values of the damping rate 0.68, 0.685, and 0.69. Figure 4 shows the simulation results.

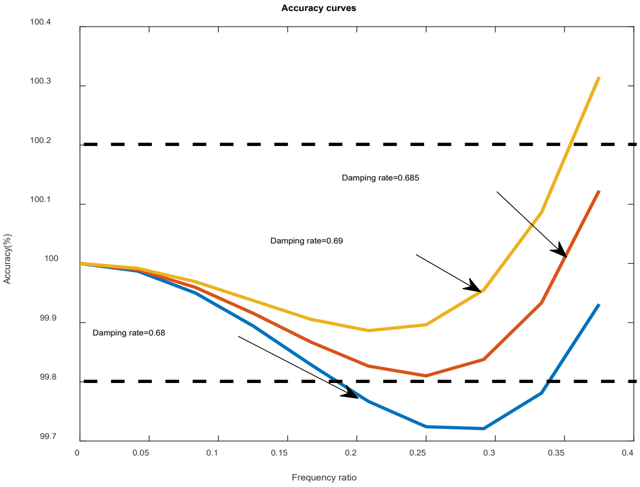

Figure 4. Simulation results of equation (17) for three values of the damping rate

It can be observed from Figure 4 that the measurement accuracy decreases with the frequency ratio for all three damping rates. However, for the damping rate of 0.68 and 0.69, the measurement accuracy does not exceed 99%. The highest measurement accuracy of 99.8% is achieved for the damping rate of 0.685. It can be concluded from this graph that the damping rate of 0.685 is the optimal value for the piezoelectric accelerometer as it provides the best measurement accuracy.

6. SIMULATION AND EXPERIMENTAL VALIDATION OF THE DEVELOPED MODEL

The developed model can be validated using simulation and experimental results. Simulation involves running the model through simulation software such as MATLAB or Simulink to compare its results with those obtained from real-world experiments. This helps assess the accuracy of the model and identify any errors or inconsistencies. Experimental validation involves conducting experiments with the model and comparing the results with real-world experiments. This process verifies the accuracy of the model and identifies any potential problems with the model. The outcomes from both simulation and experimental validation are utilized to refine the model and implement necessary adjustments to ensure its accuracy.

Table 2. Comparison of experimental and simulation tests

	Relative movement (z) (mm)	
Frequency (Hz)	Experimental tests	Simulation tests of Eq.18
0	0	0
70	0.00023	0.0003
140	0.0015	0.0010
210	0.0022	0.0023
280	0.004	0.0041
350	0.0068	0.0064
420	0.0095	0.0092
490	0.0125	0.0126
560	0.0165	0.0164
630	0.021	0.0208
700	0.0255	0.0257

The results are then plotted in a graph to assess the model's accuracy. If the error falls within acceptable limits, the model's accuracy is deemed valid.

A measurement chain consisting of a piezoelectric sensor, amplifier, and FFT analyzer enables the evaluation of vibratory displacements of an electrodynamic exciter by varying the movement frequency.

The accelerometer used in the experimental tests has the following characteristics:

- ω_0 = 2400Hz - ζ = 0.655

The relative frequency of motion varies from 0 to 700 Hz with a step of 70 Hz. The same characteristics of the accelerometer used in the experimental tests are used to simulate equation (18) and the results obtained are shown in Table 2 and Figure 5.

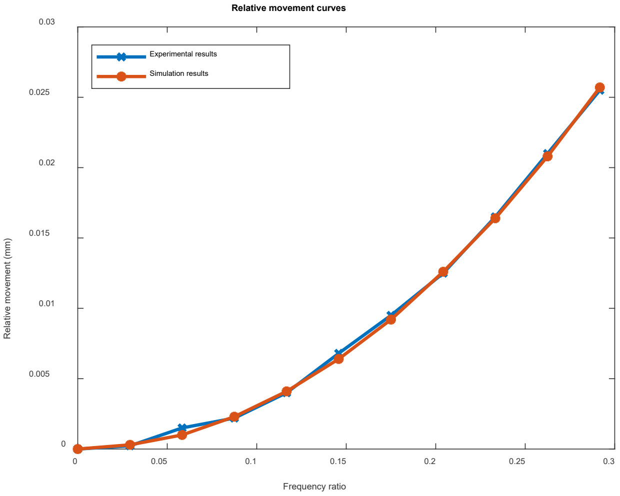

Figure 5. Results of experimental and simulation tests

From the graphs in Figure 5 and the data in Table 2, it is evident that the simulated results closely match the experimental results. This validates the model's accuracy and its ability to predict the behavior of the piezoelectric sensor effectively. The model can further be utilized to investigate the impact of various parameters such as damping rate, accuracy, and resonance frequency on the sensor's performance, facilitating optimization for enhanced performance. Moreover, the model can support the development of new designs and validate them through experimental testing.

The following figure illustrates the comparison between the measurement accuracy of the accelerometer used in the experimental tests and the accelerometer that we will propose in our design (see Figure 6).

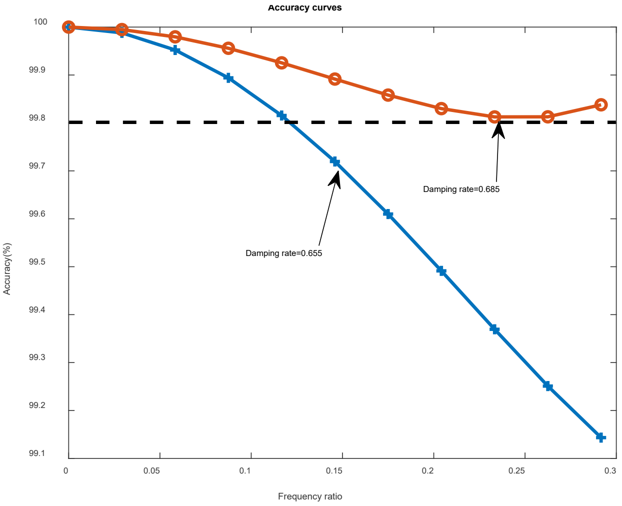

Figure 6. Comparison between two measurement accuracy one for the experimental accelerometer and the other is our proposal

Figure 6 shows two measurement accuracy curves for two damping rates, the first curve represents the accelerometer used in the experimental tests, and the second curve represents our proposed design choice. According to the results of this figure, our chosen damping rate maximizes precision at 99.8%, In contrast, the damping rate of the accelerometer used in the experimental tests achieves maximum precision at 99.15 %. Therefore, our selected damping rate enhances the accuracy of the accelerometer.

In this figure, it can be observed that when the relative frequency equals the natural frequency of the sensor, resonance occurs, resulting in an increased output signal from the sensor. To prevent this resonance, it is necessary to reduce the relative frequency below the natural frequency. Additionally, adjusting the damping coefficient of the sensor can also mitigate resonance. To explore this phenomenon, the relative frequency was varied up to 3000 Hz in the simulation, and the results are depicted in the following figure (Figure 7).

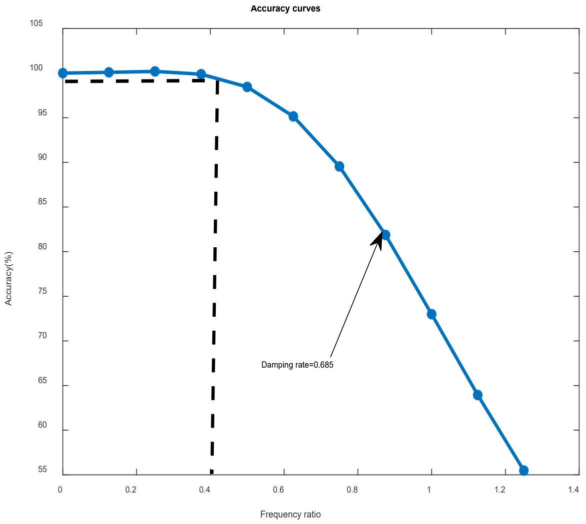

Figure 7. Measurement accuracy as a function of frequency ratio for damping rate equal to 0.685 in the resonance.

From Figure 7, it is evident that the measurement accuracy of a system is generally inversely proportional to the frequency ratio. This implies that the accuracy increases as the frequency ratio decreases. For a damping ratio of 0.685 in resonance, one would anticipate a decrease in measurement accuracy as the frequency ratio increases, ultimately reaching minimum accuracy at a frequency ratio of 1 (case of resonance).

Based on the results, an expression is proposed to mitigate the resonance effect, as illustrated by the following relationship:

$$\omega \leq 0.4\,\omega_0 \qquad (19)$$

The relationship between the frequency range of the accelerometer and its resonance effect is important for optimizing measurement accuracy. The resonance effect stems from the mechanical properties of the accelerometer and its environment. Selecting an appropriate frequency range for the accelerometer ensures it operates within the bandwidth unaffected by resonance. This enhances measurement accuracy and minimizes fault detection errors in vibration analysis, thereby improving the effectiveness of condition-based preventive maintenance.

7. CONCLUSION

The simulation results underscore the pivotal role of the damping rate in maximizing the accuracy of the piezoelectric accelerometer, achieving an impressive accuracy of 99.8% at a specific damping rate of 0.685. Additionally, to address the challenges posed by resonance phenomena, we propose a formula that expresses relative frequency as a function of the accelerometer's natural frequency.

The outcomes of this study not only contribute to the refinement of piezoelectric accelerometer performance but also hold practical implications for industries relying on electromechanical systems. By enhancing measurement accuracy, our findings pave the way for improved fault detection, thereby increasing the overall efficiency and longevity of machinery. Furthermore, the proposed techniques, validated through experimentation and simulation, advance the field of vibration analysis and bolster the practice of condition-based preventive maintenance. This research serves as a foundation for future explorations in signal processing, machine learning integration, and the further optimization of sensor parameters across diverse applications.

ACKNOWLEDGMENTS

The authors like to thank the Algerian General Direction of Research (DGRSDT) for their financial support.

REFERENCES

[1] Novoa C-G. et all, Predictive maintenance for motors based on vibration analysis with compact rio, 2017, IEEE Central America and Panama Student Conference (CONESCAPAN), 20-22 September 2017, Panama.

[2] Shin H-J. et all, Vibration Analysis and Measurements Through Prediction of Electromagnetic Vibration Sources of Permanent Magnet Synchronous Motor Based on Analytical Magnetic Field Calculations, IEEE Transactions on Magnetics, Vol. 48, No. 11, November 2012, pp. 4216–4219.

[3] Dehina W. et all, Diagnosis and Comparison between Stator Current Analysis and Vibration Analysis of Static Eccentricity Faults in The Induction Motor, 2019, 4th International Conference on Power Electronics and their Applications (ICPEA), 25-27 September, Elazig, Turkey.

[4] Hattori T. et all, Modeling method of vibration analysis model for permanent magnet motor using finite element analysis, 2009 International Conference on Electrical Machines and Systems, 15-18 November 2009, Tokyo, Japan.

[5] Kashfi M. et all, Vibration Analysis of A Wind Turbine Blade Integrated by A Piezoelectric layer, 2019 International Power System Conference (PSC), 09-11 December 2019, Tehran, Iran.

[6] Zhang Yong sheng et all, Vibration analysis of IEC 61373 standard based on measured data, 2021 7th International Symposium on Mechatronics and Industrial Informatics (ISMII), 22-24 January 2021, Zhuhai, China.

[7] Ghemari Z., Analysis and optimization of vibration sensor, IEEE International Conference on Smart Materials and Spectroscopy (SMS'2018), Tunisia, 2018, pp. 1-5, doi: 10.1109/SMS44485.2018.9101387.

[8] Ghemari Z., Upgrading of piezoresistive accelerometer response, 2016 8th International Conference on Modelling, Identification and Control, Algiers, Algeria, 2016, pp. 544-547, doi: 10.1109/ICMIC.2016.7804172

[9] Ghemari Z., S. Saad, Defects diagnosis by vibration analysis and improvement of vibration sensor measurement accuracy, Sensor Letters 17 (8), 608-613, doi.org/10.1166/sl.2019.4118

[10] Ghemari Z. et all, Improvement of the relative sensitivity for obtaining a high performance piezoelectric sensor, IEEE Instrumentation & Measurement Magazine 26 (4), 49-56, doi: 10.1109/MIM.2023.10146563.

[11] Salima Khaoula Reguieg et all, Extraction of the relative sensitivity model and improvement of the piezoelectric accelerometer performances, 2018 International Conference on Signal, Image, Vision and their Applications (SIVA), Geulma, Algeria, pp. 1-5, doi: 10.1109/SIVA.2018.8661159.

[12] Ghemari Z., Belkhiri S., Mechanical resonator sensor characteristics development for precise vibratory analysis, Sensing and Imaging 22 (1), 40, doi.org/10.1007/s11220-021-00361-3

[13] Mashimo T. et all, Vibration analysis of cubic rotary- linear piezoelectric actuator, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol.58, No. 4, April 2011, pp. 844–848.

[14] Khatri P., Visual Vibration Analysis of Vibrating Object at Low Frequency, 2021 6th International Conference for Convergence in Technology (I2CT), 02-04 April 2021, Maharashtra, India.

[15] X60-319/NF EN 13306 2010 AFNOR Terminologie de la maintenance.

[16] Ghemari Z., Modélisation, simulation et analyse expérimentale du capteur de vibration (accéléromètre)' Thèse de doctorat, 2013, Université Badji Mokhtar, Annaba, Algerié

[17] Saied R.O., Mostafa M.S., and Hussein H.A., Predictive Maintenance Program Based on Vibration Monitoring, Design and Modeling of Mechanical Systems, II- Springer, pp. 651-660, 2015. DOI: 10.1007/978-3-319-17527-0_65.

[18] Samanta B., Al-Balushi K., and Al-Araimi S., Bearing fault detection using artificial neural networks and genetic algorithm, EURASIP Journal on Applied Signal Processing, pp. 366–377, 2004. DOI: 10.1155/S1110865704310085.

[19] Lazzerini B. and Volpi S., Classifier ensembles to improve the robustness to noise of bearing fault diagnosis, Pattern Analysis and Applications, Vol. 16 (2), pp. 235–251, 2013, DOI: 10.1007/s10044-011-0209-y.

[20] Khatri P., Chhatre U. and Kadge S., Visual Vibration Analysis of Vibrating Object at Low Frequency, 2021 6th International Conference for Convergence in Technology (I2CT), Maharashtra, India, 2021, pp. 1-5.

[21] Würde A., Kahlen J. N., Langenberg N. and Moser A., Transformer Core-Vibration Analysis: Coupling Paths, 2022 IEEE Electrical Insulation Conference (EIC), Knoxville, TN, USA, 2022, pp. 1-5, doi: 10.1109/EIC51169.2022.9833177.

[22] Xu H. -m. and Wang B., Vibration Analysis of High Pressure Mud Piping Systems and Vibration Reduction Method, 2020 3rd World Conference on Mechanical Engineering and Intelligent Manufacturing (WCMEIM), Shanghai, China, 2020, pp. 732-737, doi: 10.1109/WCMEIM52463.2020.00157.

[23] Li C., Li J., Fang X. L., Tang Y., Deng T. and Lu Y., Application of a Method of Identifiying Instantaneous Shaft Speed from Spectrum in Aeroengine Vibration Analysis, 2022 Global Reliability and Prognostics and Health Management (PHM-Yantai), Yantai, China, 2022, pp. 1-7, doi: 10.1109/PHM-Yantai55411.2022.9942056.

[24] Krishnan G. et all, Micromachined High-Resolution Accelerometers, Journal of the Indian Institute of Science,Vol. 87, No. 3, 2007, pp. 333-361.

[25] Mituletu I.C., Gillich G.-R., Nuno M.M. Maia, A method for an accurate estimation of natural frequencies using swept-sine acoustic excitation, Mechanical Systems and Signal Processing, Vol.116, 2019, pp. 693-709.

[26] Ghemari Z., Saad S., Development of model and enhancement of measurement precision of sensor vibration, IEEE Sensors Journal 12/2012, 12(12), pp. 3454-3459, doi:10.1109/JSEN.2012.2210789

[27] Ghemari Z., Improvement of the piezoelectric sensor by the progress of the measurement accuracy, IEEE International Conference on Smart Materials and Spectroscopy (SMS'2018), Yassmine Hammamet (Tunisia), 10/2018.

[28] Ghemari Z. et all, New Model of Piezoelectric Accelerometer Relative Movement Modulus, Transactions of the Institute of Measurement and Control, 2015;37(8), pp. 932-941, doi:10.1177/0142331214549572

[29] Ghemari Z., Saad S., Modeling and enhancement of mechanical sensitivity of vibration sensor, Journal of Vibration and Control, 2014; 20(14), pp. 2234-2240. doi:10.1177/1077546313486507.

[30] Ghemari Z. et all, New Formula for the Piezoresistive Accelerometer Motion Acceleration and Experimental Validation, Journal of Advanced Manufacturing Systems, Vol. 16, No. 01, pp. 57-65 (2017) DOI: 10.1142/S0219686717500044.

[31] Ghemari Z., Saad S., Reducing the measurement error to optimize the sensitivity of the vibration sensor, IEEE Sensors Journal, 14 (5), pp. 1527-1532, doi: 10.1109/JSEN.2014.2298493.

[32] Ghemari Z., Saad S., Improvement of piezoresistive accelerometer performance, 3rd International Conference on Systems and Control, Algiers, 2013, pp. 759-762, doi: 10.1109/ICoSC.2013.6750943.

[33] Ntakpe J.L., Gillich G.R., Mituletu I.C., Praisach Z.I., Gillich N., An Accurate Frequency Estimation Algorithm with Application in Modal Analysis, Romanian Journal of Acoustics and Vibration 13 (2), pp. 98-103, 2016.

[34] Gillich N., Tufisi C., Sacarea C., Rusu C.V., Gillich G-R, Praisach Z-I, Ardeljan M., Beam Damage Assessment Using Natural Frequency Shift and Machine Learning. Sensors, 2022; 22(3), 1118, https://doi.org/10.3390/s22031118

[35] Xu, Qin, Wei Huang, Hao Zhen Wu, Jun Yuan Wang, and Jie Yu Liu, Study of Crack Width of the Fiber Reinforced Polymer Beam, Advanced Materials Research. Trans Tech Publications, Ltd., May 2011. https://doi.org/10.4028/www.scientific.net/amr.243-249.806.