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SENSING THE VIBRATIONS OF GRINDING WHEELS BY CONTACT AND NON-CONTACT METHODS

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Abstract

This study explores vibration diagnostics and balancing techniques for grinding wheels using non-contact measurement technologies. It focuses on the impact of static balancing on vibration reduction, measured with a laser interferometer for high-frequency resolution. Theoretical foundations of technical diagnostics and the application of FFT (Fast Fourier Transform) for vibration analysis are discussed. Contact and non-contact methods are compared, with experimental data demonstrating the superior accuracy of non-contact approaches. Results confirm that proper balancing enhances operational stability and extends tool life. The study highlights the benefits of non-contact diagnostics for predictive maintenance and improved reliability in industrial rotating equipment.

Keywords:

Technical Diagnostics, Grinding Wheel, Predictive Maintenance, Vibration Diagnostics, Imbalance

1 INTRODUCTION

Ensuring operational stability and high quality of the machined surface is an integral part of efficient production in modern mechanical engineering. Vibration phenomena that occur during rotary processes represent a serious problem affecting not only the machining process itself, but also the service life of tools, surface quality and energy consumption of the system. In the field of grinding, where high contact forces occur between the tool and the workpiece, vibrations have a direct impact on the stability of the process, the resulting surface roughness and the probability of microdamage [Bratan 2022]. One of the main causes of excessive vibrations is the imbalance of grinding wheels, which is often a result of manufacturing inaccuracies, uneven wear or incorrect assembly. Static and dynamic imbalances cause increased vibration amplitudes and thus deterioration of technological results. In parallel, intensive research is being conducted focused on modeling and prediction of these phenomena, often using advanced numerical and simulation tools. For example, Feng et al. [Feng 2023] simulated the surface topography after grinding, taking into account wheel wear and its vibration behavior, confirming that the dynamic characteristics of the tool significantly affect the resulting surface microgeometry.

Vibration stability was also addressed by Zhu et al. [Zhu 2023], who investigated the process of polishing aircraft engine blades using a pneumatic grinding wheel controlled by a robot. The results pointed to the significant role of vibration control in machining parts with high precision. In the context of predictive maintenance, the study by Charde et al. [Charde 2025] presents advanced models for predicting surface roughness using machine learning, reflecting the growing integration of AI technologies in the field of manufacturing systems.

The connection between vibration phenomena and thermal-mechanical behavior during grinding was also demonstrated by the work of Hu et al. [Hu 2024], which quantifies the influence of the interaction of individual particles on the resulting surface roughness. This approach confirms the complexity of the grinding process, in which mechanical, thermal and dynamic factors accumulate. From the point of view of vibration control as a systemic phenomenon, the work of Yadav et al. [Yadav 2023], who proposed a vibration damping model using a wheel replacement with special dynamic properties, an approach applicable in the broader context of rotating systems design.

In summary, the current literature points to the need for an integrated approach to vibration diagnostics and control during grinding. Many studies confirm the benefits of using non-contact measurement methods, especially due to their higher accuracy, speed and ability to capture even subtle changes in system behavior [Marinkovic 2024]. At the level of materials research, the importance of detailed local analysis of mechanical properties is manifested, for example, in the evaluation of structural changes induced by physical influences. An example is the study by Janostik et al. [Janostik 2023], which dealt with the effect of irradiation on the mechanical properties of cross-linked polypropylene. In this case too, it turns out that detailed material diagnostics is necessary for understanding the complex behavior of material structures under load, both in static and dynamic modes. On this basis, this study focuses on the experimental evaluation of the effect of static balancing of grinding wheels on vibration amplitudes using vibration diagnostics, specifically using laser interferometry. It also compares contact and non-contact measurement methods and monitors their impact on diagnostic accuracy and potential for use in predictive maintenance.

2 METHODS

The experimental part of the study focused on the vibration analysis of grinding wheels in order to assess the effect of static balancing on their dynamic behavior during grinding. Two different methods were used to measure vibrations: contact and non-contact. The aim was not only to evaluate the effect of balancing on the vibration amplitude, but also to compare the accuracy and reliability of both approaches in real operating conditions.

2.1 Experimental setup and balancing

The measurements were carried out on a conventional BRH 20.03F surface grinder with a fixed table and horizontal spindle, at a nominal spindle speed of 2550 rpm. The machine was located in standard workshop conditions, with a controlled microclimate to minimize the influence of ambient vibrations and temperature fluctuations.

Before the measurement itself, the grinding wheel was statically balanced. The procedure consisted of placing the wheel on a low-friction balancing shaft and subsequently adding weights to the balancing holes. The goal was to minimize the eccentricity of the mass in one plane of rotation. Balancing was considered successful when the wheel spontaneously rotated after it was released.

2.2 Vibration measurement

Vibrations were recorded by two parallel methods:

Contact method using a piezoelectric accelerometer mounted directly on the grinder body near the spindle housing. The accelerometer signal was processed using a high-resolution A/D converter.

Non-contact method using a laser interferometer operating on the Michelson arrangement principle. The system consisted of a laser source, optical prisms, a semi-transparent mirror and a detector. The measured value represented the relative change in the optical path length caused by the oscillation of the wheel surface.

Experimental setup of vibration measurement using a laser interferometer. The image shows the interferometric sensor positioned opposite the grinding wheel mounted on the spindle of the BRH 20.03F surface grinder. The contact sensor (accelerometer) was mounted on the spindle housing (not visible in this view). The optical path was aligned to measure the first harmonic component of vibration during rotation (fig.1).

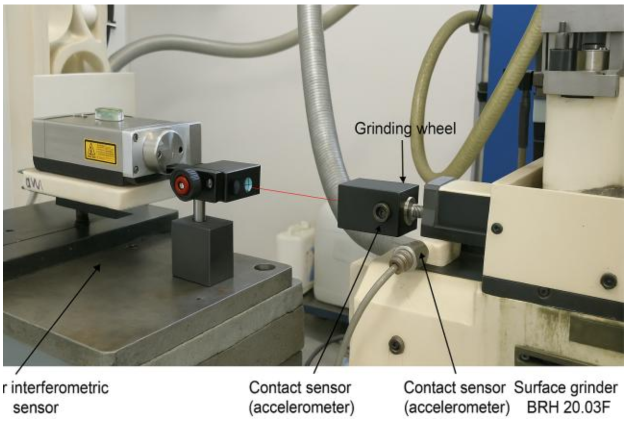

Fig. 1 Experimental setup for vibration measurement using a laser interferometer.

The sampling frequency was set to 1 kHz with a measurement duration of 11 seconds, which corresponds to 11.000 samples per measurement. Each method was repeated 100 times, with identical working conditions maintained between each cycle – constant cutting depth and feed, and continuous coolant application.

Distance vs. Time plot fig. 2 obtained from the non-contact vibration measurement. The signal represents the amplitude of the first harmonic component of the grinding wheel vibration over time, captured by a laser interferometer. The increased amplitude in the later segment of the signal corresponds to higher dynamic imbalance before static balancing.

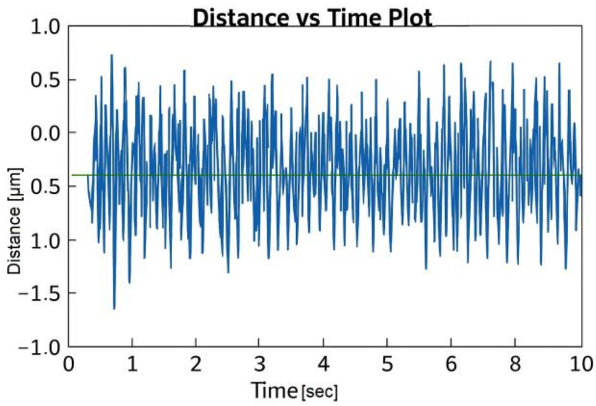

Fig. 2 Time course of vibrations recorded by non-contact method.

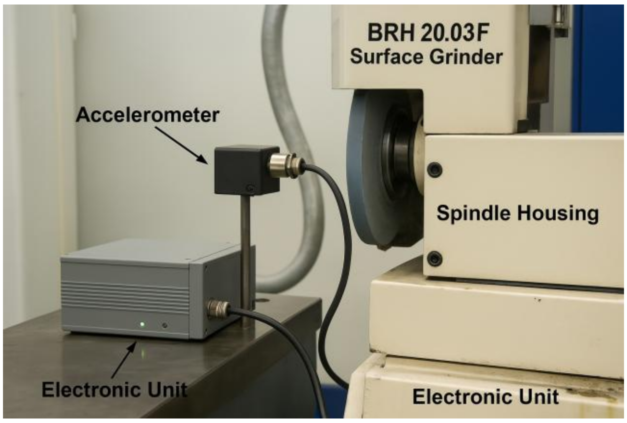

Fig. 3 Contact measurement.

For comparison with the non-contact method, the vibration analysis was supplemented with measurements using a contact piezoelectric accelerometer. (Fig. 3) This sensor was firmly attached to the spindle bearing housing of the BRH 20.03F grinder near the grinding wheel. The attachment was made using a special magnetic holder, which ensured stable contact without movement or resonance during the measurement.

The signal from the accelerometer was fed to a measuring unit with an integrated analog-to-digital converter, which recorded vibration values in the time domain. The data were further processed in the Minitab environments, where spectral analysis (FFT) and statistical evaluation of the first harmonic component were performed.

The contact method allowed for direct measurement of vibrations of the grinder body at the point where forces are transferred from the rotating wheel. Although this method is susceptible to influence by structural resonances and mechanical damping, it provided stable outputs with lower variability compared to the non-contact method. The results served as a reference basis for evaluating the sensitivity of both approaches.

2.3 Data processing

The obtained data were analyzed using the software tools Minitab. In Minitab, spectral analysis of signals was performed using the fast Fourier transform (FFT), which allowed the identification of dominant frequency components and the determination of the main sources of vibrations. In particular, the amplitude of the first harmonic component was monitored, which was considered to be the dominant component associated with mechanical imbalance.

Statistical data processing was performed in the Minitab environment. In the first phase, normality tests (Shapiro-Wilk), descriptive statistics and subsequently the F-test were performed to compare variances. Then, a two-sample t-test was applied to determine a statistically significant difference in the mean values of vibration amplitudes between both methods. The values were interpreted at the significance level α = 0.05.

A nonlinear regression analysis was performed to examine the relationship between the amplitude of the first harmonic component and the dynamic behavior of the system. The regression model utilized the natural logarithm of the amplitude, reflecting the typical logarithmic relationship between vibration energy and system response. his analysis aimed to evaluate how changes in vibration amplitudes correlate with variations in the stability of the grinding process.

2.4 Calibration and verification of measurements

Before starting the series of measurements, a calibration test of both measuring systems was performed. For the accelerometer, linearity and sensitivity were checked using a standardized vibration excitation device. For the laser interferometer, path sensitivity parameters and reproducibility accuracy were verified. The measuring systems were stabilized before each measurement and checked for possible signal drift.

3 RESULTS

The measurement of the first harmonic component of vibrations using the contact and non-contact methods yielded a comprehensive data set that allowed a comparison of the accuracy, variance, and diagnostic value of both approaches. Within each method, 100 repetitions were performed under identical conditions. The obtained data were subsequently analyzed in terms of basic statistical characteristics, normality of distribution, variance, and mean values.

3.1 Descriptive statistics

In the non-contact method, compared to the contact method, more pronounced amplitudes and a larger signal amplitude appear in the time series. This reflects the higher sensitivity of the laser interferometer, which is not affected by mechanical attenuation or resonant properties of the sensor attachment.

To evaluate the basic characteristics of the measured data, descriptive statistics were performed for both vibration measurement methods – contact and non-contact.

The vibration time course graph (Fig. 4) shows the development of the amplitude of the first harmonic component over time for each of the measured methods. The graph shows that the contact method shows relatively stable and less variable amplitude values, while the non-contact method shows larger amplitudes and greater fluctuations in values during the measurement. This reflects the higher sensitivity of the non-contact method, which can capture even subtle changes in vibrations.

The contact method showed an average value of the amplitude of the first harmonic component of 1.0038 µm, with a standard deviation of 0.0978 µm and a coefficient of variation of 9.75%. The non-contact method showed an average value of 1.2949 µm with a larger standard deviation of 0.1333 µm and a coefficient of variation of 10.29%. This means that the non-contact method showed higher average values, while being more sensitive to changes in vibration amplitudes, which confirms its greater ability to capture subtle changes in system behavior.

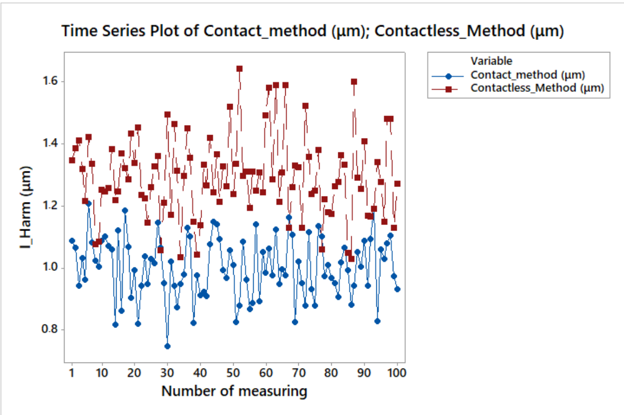

Fig. 4 Vibration time graph.

The minimum and maximum values for the contact method were 0.7493 µm and 1.2097 µm, while for the non-contact method they were 1.0290 µm and 1.6436 µm. This range indicates a wider variability for the non-contact method.

From the boxplot (fig.5) it is clear that the non-contact measurement method (laser interferometry) shows a higher median amplitude of the first harmonic component than the contact method. Specifically, the median for the non-contact method is approximately 1.29 µm, while for the contact method the median is lower, approximately 1.01 µm. This difference also corresponds to the calculations of the average values within the descriptive statistics. It is also clear that the dispersion of the values for the non-contact method is larger, which is confirmed by both the longer “whiskers” and the wider box, which represents the interquartile range (IQR). This higher variability is consistent with the results of the F-test, which demonstrated a statistically significant difference in variances between the two methods. The boxplot also shows that the contact method provides a narrower range of values and less variability in measurements. This can be interpreted as a consequence of the lower sensitivity of this method to subtle vibrational deviations. If outliers are present in the graph, their presence is considered to be statistically acceptable fluctuations due to the normal distribution of the data.

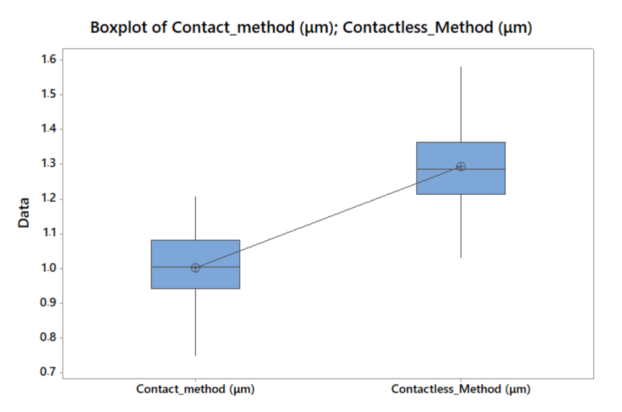

Fig. 5 Boxplot diagram.

Overall, the graph confirms that the non-contact method provides higher amplitudes and variability, indicating its greater ability to capture dynamic phenomena related to microvibrations and system response to unbalance.

Tab. 1 Descriptive statistics of the amplitude of the first harmonic component of vibrations obtained by the contact and non-contact method.

	Total Count	Mean	St. Dev.	Coef. Var.	Min.	Q1	Median	Q3	Max.	Range
Contact Method (µm)	100	1.0038	0.0978	9.75	0.7493	0.9438	1.0059	1.0834	1.2097	0.4604
Contactless Method (µm)	100	1.2949	0.1333	10.29	1.0290	1.2154	1.2872	1.3653	1.6436	0.6145

The basic parameters of the data distribution are given: number of measurements (N), arithmetic mean, standard deviation (StDev), coefficient of variability (CoefVar), minimum, quartiles (Q1, median, Q3), maximum, range and interquartile range (IQR).

Table 1 shows that the non-contact method shows a higher mean value of vibration amplitude (1.2949 µm) than the contact method (1.0038 µm), which indicates a higher sensitivity of the non-contact system to detect vibrations. It is also evident that the data dispersion (measured using standard deviation and IQR) is higher for the non-contact method. The standard deviation is 0.1333 µm for the non-contact method compared to 0.0978 µm for the contact method. The coefficients of variability (about 10% for both methods) show a relatively low dispersion relative to the mean, which indicates a good quality of the measurement. The range of values is also larger for the non-contact method (0.6145 µm) than for the contact method (0.4604 µm), which further confirms the higher amplitude dynamics captured by laser interferometry.

The normality testing also included a visual analysis using probability plots, which complement the numerical results of the Shapiro-Wilk test. In these plots, individual measured values are plotted against the theoretical normal distribution. If the points in the plot lie approximately along a straight line, the distribution can be considered normal.

For both methods – contact (Fig. 6) and non-contact (Fig. 7), the points in the plot have an almost linear course without significant deviations, which indicates compliance with the normal distribution. There are no systematic curvatures or significant outliers that would signal a deviation from the theoretical distribution.

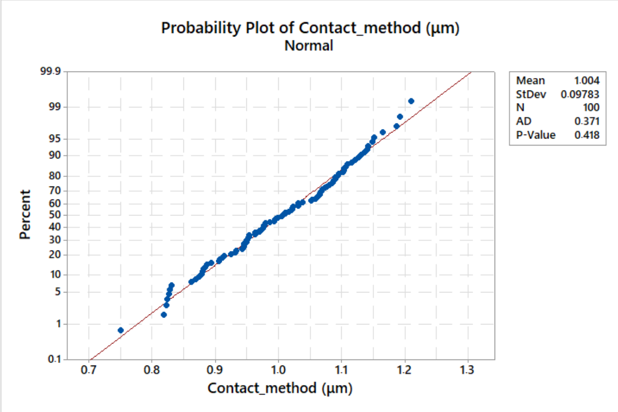

Fig. 6 Probability plot of contact method.

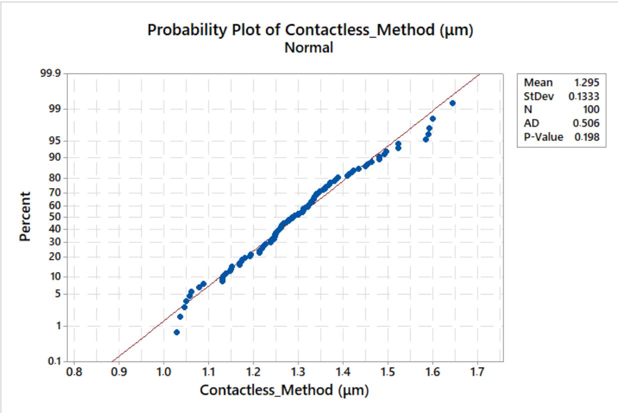

Fig. 7 Probability plot of contactless method.

This visual information thus supports the conclusion of the Shapiro-Wilk test that both data sets meet the assumption of normality. As a result, it was possible to continue the analysis using parametric statistical methods such as the F-test and the two-sample t-test.

3.2 F-test – comparison of variances

A two-sample F-test was used to compare the variability of the measured values between the contact and non-contact methods. This test verifies whether the variances of both sets are statistically identical or whether they differ significantly. At the significance level α = 0.05, the hypothesis was tested:

- H_0 (null hypothesis): The variances of both methods are the same.
- H_1 (alternative hypothesis): The variances differ.

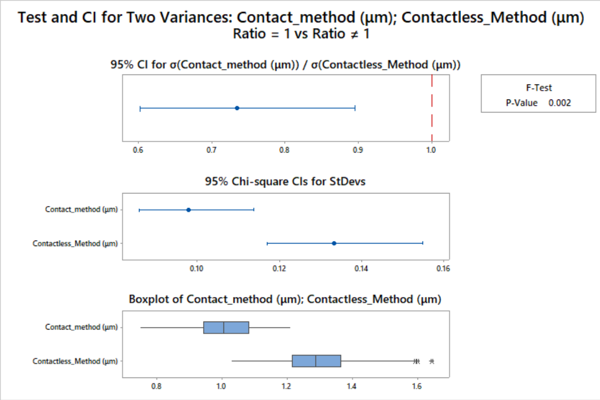

Fig. 8 F-test of variance.

The resulting test statistic was F = 0.54, with a p-value = 0.002. Since the p-value is smaller than the chosen significance level, the null hypothesis was rejected. This means that the variances differ significantly between the methods. The higher variance for the non-contact method confirms its higher sensitivity, but also greater variability of the measurement (fig. 8).

3.3 t-test – comparison of average values

After verifying the normality of the data and determining the difference in variances, a two-sample t-test was performed to compare the average values of the amplitude of the first harmonic component of vibrations between the two methods. The test evaluated the following hypothesis:

- H_0: The mean values are the same.
- H_1: The mean values are different.

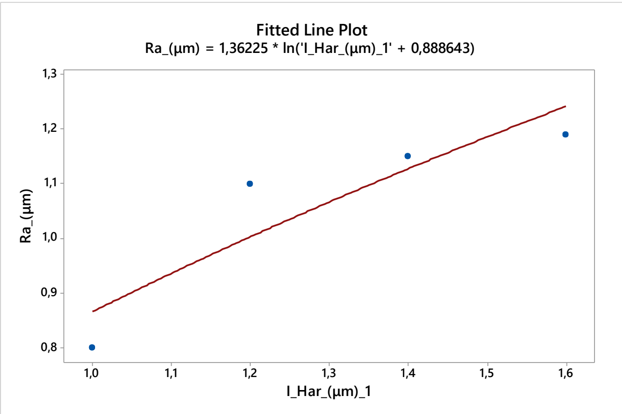

Fig. 9 t-test.

The difference in diameters was -0.2910 µm, the 95% confidence interval for this difference was (-0.3237; -0.2584). The resulting p-value = 0.000, which means that the difference is statistically significant. The non-contact method therefore systematically measures higher vibration values than the contact method (fig.9).

3.4 Regression analysis – dependence of Ra on vibration amplitude

The experiment also evaluated the dependence between the amplitude of the first harmonic component of vibrations and the resulting surface roughness Ra. A nonlinear regression equation of the form was used:

$$Ra_{(\mu m)}=1,36225 \cdot ln(A_{1.har}+0,888643) \qquad (1)$$

where $A_{1.har}$ denotes the amplitude of the first harmonic component.

The results of the regression analysis showed that there is a logarithmic relationship between the vibration amplitude and the Ra values. As the vibration signal amplitude increases, the surface quality deteriorates. This relationship supports the hypothesis that higher vibrations (e.g. due to disc imbalance) negatively affect the final quality of the machined surface.

4 DISCUSSION

The results of this study clearly confirm that the vibration measurement method has a significant influence on the obtained amplitude values and the subsequent assessment of the technical condition of grinding wheels. The non-contact method based on laser interferometry showed not only higher average values of the amplitude of the first harmonic component, but also greater variability of the measurement compared to the contact piezoelectric method. This fact confirms the hypothesis that the non-contact measurement is more sensitive to capturing small oscillations, which can be partially suppressed by mechanical attenuation and the sensor's natural frequency in the contact method. The differences between the two methods were statistically confirmed using the F-test and the two-sample t-test, and in both cases the null hypotheses were rejected at the significance level α = 0.05. The higher dispersion in the non-contact method is in accordance with what is stated by Feng et al. [Feng 2023], who also took into account the effect of wheel wear and its vibration response when simulating the surface topography. The increased sensitivity of the non-contact system thus allows for the capture of micro-level interactions between the tool and the workpiece, which have a direct impact on the output surface quality. Compared to the findings of Feng et al. (2023), who used simulation to assess the influence of wheel wear on vibration patterns, our experimental results provide empirical evidence supporting the hypothesis that vibration amplitude significantly affects the stability of the machining process. In contrast to the work of Hu et al. (2024), which highlighted the thermal-mechanical interactions during grinding, our study primarily focuses on vibration-induced instability, confirming that controlling vibrations through balancing can significantly enhance surface quality. This direct experimental validation offers a practical perspective that complements the simulation-based approaches of previous studies.

The logarithmic dependence between the vibration amplitude and the surface roughness Ra indicates a direct relationship between the dynamic behavior of the wheel and the quality of the machined surface. This relationship is also supported by the work of Hu et al. [Hu 2024], which demonstrated a connection between the thermal-mechanical behavior during grinding and the resulting surface quality. Higher vibration amplitudes therefore affect not only the operational stability, but also the functional properties of the workpiece. This relationship is especially important for components where roughness is a key parameter for subsequent functions such as friction, tightness or surface treatment. The importance of vibration stability for machining process control is also confirmed by the study of Zhu et al. [Zhu 2023], which focused on the polishing of aerospace components using a robotic wheel. The authors state that even small changes in tool oscillation can cause critical deviations in shape accuracy, which corresponds to the need for a reliable diagnostic system. In this context, the advantages of the non-contact method can be seen not only in accuracy, but also in the possibility of its integration into predictive maintenance, as indicated, for example, by the work of Charde et al. [Charde 2025].

At the same time, the results show that the classical contact method, although less sensitive, provides stable and reproducible data with less dispersion. This indicates its suitability for basic operational monitoring of vibrations in normal operation, where simplicity, low cost and robustness of measurement are required. This puts the two methods in a complementary relationship – contact sensing can serve for continuous monitoring, while non-contact analysis is used in critical diagnostic applications. Despite the observed variability in the non-contact method, it is essential to recognize that its increased sensitivity makes it particularly valuable in applications where capturing subtle oscillatory changes is crucial. For high-precision applications, such as optical or aerospace industries, where even minimal deviations can compromise product quality, the ability of laser interferometry to detect micro-vibrations justifies its use. The contact method, while more stable, may not be able to detect these minute changes, which makes the non-contact approach superior in contexts where maximum sensitivity is required.

A limitation of this study can be considered the fact that the experiments were performed only in a statically balanced state of the wheel and with constant cutting parameters. Considering the influence of dynamic balancing, variable loading or different types of abrasive materials could further expand the applicability of the obtained knowledge. It would also be appropriate to examine the influence of different types of bearings, machine frame damping and connections to other structural parts. Furthermore, it is important to acknowledge that the exclusive focus on static balancing may limit the generalizability of the findings. Incorporating dynamic balancing methods could reveal additional insights into the dynamic behavior of grinding wheels under varying operational stresses. Future research should also investigate how variable cutting conditions might influence the stability and vibration characteristics, as these factors are often present in practical industrial applications.

From the point of view of industrial use, non-contact vibration diagnostics is attractive primarily for highly accurate and automated applications, where it is necessary to monitor changes in vibration behavior in real time without interfering with the machine structure. The results of this study thus provide important insights not only for the scientific community involved in technical diagnostics, but also for practical engineers who are looking for effective tools for ensuring stability and predictive maintenance of rotating equipment. The presented experimental validation supports the hypothesis that proper balancing significantly reduces vibration amplitudes, thereby improving the stability and longevity of the grinding process.

5 CONCLUSION

This study focused on comparing contact and non-contact methods of vibration measurement of grinding wheels with the aim of evaluating the effect of static balancing on the amplitudes of the first harmonic component and at the same time examining how different methods affect the accuracy and dispersion of the measurements. 100 repeated measurements were performed for each method, with the non-contact method using a laser interferometer showing higher sensitivity, a wider range of values and higher amplitudes than the contact method based on a piezoelectric accelerometer.

The results showed that the differences between the methods are statistically significant – both in terms of dispersion (F-test) and average values (t-test). These findings confirm that the choice of measurement method has a fundamental impact on the interpretation of the technical condition of the machine. The non-contact method allows for more detailed monitoring of microvibrations and is therefore more suitable for sophisticated vibration diagnostics, while contact measurement provides more stable outputs with less variability, making it suitable for routine inspection. Despite the higher variability observed in the non-contact method, its enhanced sensitivity makes it particularly valuable in applications requiring high precision. Industries such as optics, automotive, and aerospace demand meticulous control over micro-vibrations, where even small oscillations can compromise product quality. In such contexts, the ability of laser interferometry to detect fine dynamic changes justifies its implementation despite the observed variability.

A significant finding is the confirmed logarithmic dependence between the vibration amplitude and the resulting surface roughness Ra. This correlation shows that increased vibrations, caused for example by disc imbalance, have a direct impact on the quality of machining. This relationship is important for understanding the interaction between the mechanical behavior of the machine and the functional properties of the workpiece. It confirms the necessity of monitoring vibrations not only from the point of view of machine protection, but also for the sake of the output quality of the product.

From the point of view of practical application, the results can be used when setting predictive maintenance strategies in production facilities, where stable and reproducible grinding is a priority. The non-contact method is suitable for use in high-precision applications (e.g. optical, automotive or aerospace industries), where even minimal vibrations can negatively affect the function of parts. The contact method, on the other hand, remains an economical alternative for facilities that require quick and simple monitoring of the condition of equipment.

The study also showed that the application of simple static balancing brings a measurable improvement in vibration stability. Balancing is not only a question of mechanical comfort, but also has a direct impact on the quality of machining and tool life. In this regard, it would be appropriate to monitor the influence of dynamic balancing, changes in cutting conditions or the use of different types of abrasive materials in future research. It would also be beneficial to investigate the influence of vibrations under real load with the participation of different types of workpieces, machines and supporting structures. While the study effectively demonstrates the influence of static balancing on vibration amplitudes, it is important to recognize that real industrial conditions often involve dynamic balancing and varying cutting parameters. Future studies should address these aspects to provide a more comprehensive understanding of grinding wheel behavior under operational loads. Additionally, exploring different materials and abrasive types could further enhance the practical relevance of the findings.

Overall, vibration diagnostics has proven to be a valuable tool for assessing the technical condition of machinery, predicting wear, and optimizing production processes. The use of non-contact methods introduces new possibilities for accurate and reliable diagnostics, significantly contributing to the concept of intelligent maintenance within the framework of modern industry 4.0. From a practical perspective, implementing non-contact vibration diagnostics in high-precision manufacturing environments can enhance predictive maintenance strategies. Integrating such systems into automated monitoring can facilitate early detection of mechanical instabilities, reducing downtime and improving process reliability. To further substantiate these benefits, conducting long-term case studies in real production environments is recommended.

6 ACKNOWLEDGMENTS

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