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Time-domain analysis based on the electromechanical impedance method for monitoring of the dressing operation

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Abstract

Among the methods used in structural health monitoring (SHM), the electromechanical impedance technique (EMI), which uses piezoelectric transducers of lead zirconate titanate (PZT), stands out for its low cost. Then, this paper presents a new approach for monitoring of the dressing operation from the digital processing of voltage signals based on the time-domain response of a PZT transducer by EMI method. Experimental tests of the dressing process were performed by using a single-point dresser equipped with a natural diamond. The voltage signals in the time-domain were collected in different damage levels. By using temporal statistics, it was possible to qualify different damage levels that the diamond suffered during the dressing operation, observing variations from the magnitude of the signals. The dressing operation is of utmost importance for the grinding process and the dresser wear negatively affects the result of the process, which owns high added value. In this way, this work contributes with a new monitoring tool which aims ensuring a consistent dressing operation.

Keywords: Manufacturing system, digital signal processing, electromechanical impedance, dressing operation.

1. Introduction

Usually, human operators do the monitoring of the dresser tool condition. However, researches own a great interest to develop technologies that would be able to automatically monitor that condition, contributing effectively for the grinding process optimization [1].

Nomenclature

ANN	Artificial Neural Networks
C_0	Static capacitance
CAD	Computer Aided Design
CCDM	Correlation Coefficient Deviation Metric
DAQ	Data Acquisition System
EMI	Electromechanical Impedance
K	Wave-number
ℓ	Size of patch
N	Amount of discrete data
NI	National Instruments
PZT	Lead Zirconate Titanate
RMS	Root Mean Square
RMSD	Root Mean Square Deviation
SHM	Structural Health Monitoring
ω	Angular frequency
x	Raw signal
x_{RMS}	RMS signal
Z_E	Electrical impedance
Z_S	Mechanical impedance of the monitored structure
Z_T	Mechanical impedance
$\|\|$	Parallel connection

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It is known that the topography and the conditions in which the grinding wheel is prepared in the dressing process have a profound influence on the grinding performance. That fact directly influences the finishing of the parts [2]. In this way, dressing is the process that guarantees the quality of the grinding within the required parameters, because it is responsible to recondition the grinding wheel when it loses its cutting capacity. To dress conventional grinding wheels, it is usually used diamond single-point dresser. However, as the dressing process occurs, the diamond wears out, which could provide less roughness on the grinding wheel. Therefore, an online monitoring system could control the condition of the grinding wheel and eliminate undesirable conditions of the process [1], [3], [4].

On the other hand, monitoring systems for structural integrity (SHM) in real time are essential for machining processes, such as grinding and dressing processes. Nowadays, these kinds of systems are indispensable for automated systems because there is a need of big productivity, high quality and low costs. Among the methods used in SHM, the electromechanical impedance (EMI) technique, which uses piezoelectric transducers of lead zirconate titanate (PZT), stands out because of its low price. The EMI method has been used for several applications, such as structures, machines, tools and machining processes [5]–[12].

Up to the present time, researches about EMI method applied on the dressing process were not found, making innovative the approach brought out by this work. Furthermore, the various researches performed at monitoring systems by using EMI care about the real part, imaginary part or the magnitude of the impedance signatures, which are necessary to detect failures. Nevertheless, the signal in the time-domain obtained from the impedance measurement through electrical voltage values has not been so studied.

Therefore, the objective of this paper is to monitor the wear condition of single-point dressers of natural diamond through the time-domain analysis from EMI method measurements, using low cost transducers of PZT type. By means of statistics commonly used in signal processing in the time-domain, such as mean value and root mean square (RMS), which are classical tools but have never been studied for EMI method, it is intended to evaluate the damage levels (wear) of the diamond, contributing for the dressing operation monitoring. This paper presents a simple, direct and economic form of monitoring, which looks for a threshold that identifies the correct moment in which the dressing tool should be replaced.

1.1. Electromechanical Impedance (EMI) method

The operation principle of the EMI method is based on the piezoelectric effect that stablishes an electromechanical coupling between structure and transducer fixed on it [6], [13]. A PZT ceramic glued on a structure is excited by a low frequency alternating current. In terms of electrical impedance of the piezoelectric transducer, many solutions have been proposed based on two-dimensional and three-dimensional propagation ways. However, if the thickness of the sensor is small, about fractions of millimeters, deformation across its thickness is little expressive. The electrical impedance of the transducer can be calculated by Equation (1) [8], [9].

$$Z_E(\omega)=\frac{1}{j\omega C_0}\left\|jZ_T\left(\frac{s_{11}}{d_{31}\ell}\right)^2\left[\frac{1}{2}\tan\left(\frac{k\ell}{2}\right)-\frac{1}{\sin(k\ell)}+\frac{Z_S}{j2Z_T}\right]\right. \tag{1}$$

Where $Z_E(\omega)$ is the electrical impedance, ω is the angular frequency, C_0 is the static capacitance for a square patch of size ℓ, k is the wave-number, Z_T is the mechanical impedance of the piezoelectric patch, Z_S is the mechanical impedance of the monitored structure, d_{31} is the piezoelectric constant, s_{11} is the compliance at a constant electric field, ‖ indicates a parallel connection, and j is the unit imaginary number.

Throughout the last decades, the use of PZT transducers to control vibrations and noises, as well as damage detection for SHM applications, has been gaining increasing importance [14]. One of the advantages of these transducers is certainly its low cost and great accessibility. This type of transducer has importance in many monitoring techniques and are ordinarily built of PZT ceramic or Macro-Fiber Composite (MFC), which has thickness of about tenths of millimeters [15].

The use of piezoelectric transducers PZT type is still rare in manufacturing systems. Ribeiro e*t al.,* [16] analyzed the workpiece surface with regard to its surface roughness and burn occurrence by using a PZT as an alternative to the conventional AE sensor widely used in grinding process monitoring. The results showed a strong correlation among the characteristics extracted from the collected signals, the behavior of the surface roughness of the workpieces and the burn occurrence.

1.2. Damage detection in the time-domain based on the impedance

Although very little has been published about this subject, it is known that time-domain analysis methods are sensible to detect structural damages when compared to the frequency-domain analysis of the EMI method. The efficiency of the time-domain method is on the damage detection and not on its exact location [17], [18]. Inman et al. [17] used the wavelet transform to successfully detect damages, comparing to the frequency response of the EMI by using RMSD (root mean square deviation) and CCDM (correlation coefficient deviation metric) indices. Time-domain analysis is composed by the excitation circuit on the PZT/structure, which is proposed by [8], and represented in Figure 1.

In general, damage detection in the time-domain is based on the comparison of the electric voltage variations from the signals response of the PZT transducers glued on the monitored structure.

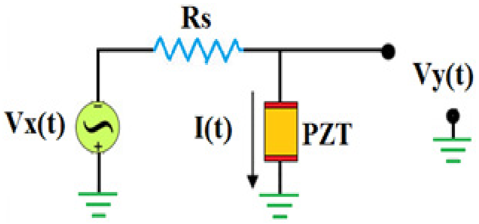


Fig.1. Excitation and response circuit of the PZT/structure set

In the same way as the frequency analysis by EMI method, in the time-domain it is also necessary to compensate the effects of temperature, or even keep it constant during impedance measurements, avoiding false positive diagnosis [17], [19], [20].

1.3. Monitoring of the dressing process

Monitoring and control systems for machining process seek to attend the needs arising from material hard to deal with, such as diamonds of the dressers in the dressing operation. Indirect methods that depend on the relationship between tool condition and measured signals (such as force, acoustic emission (AE), vibration, electric current etc) have been extensively studied for monitoring of the grinding process.

To monitor dressing operation, it is important to mention D'Addona et al. [21] research, which proposed a methodology to characterize the wear level of the single-point synthetic diamond by using vibration signals and artificial neural networks (ANNs). Results showed an efficient method to monitor the dressers wear, but the approach was limited at just one model composed by two inputs and just two frequency bands. Then, the research was expanded in [1], where several ANN models were studied, combining from one, two and three inputs for seven frequency bands of the vibration signals, concluding a wide approach for this subject.

The RMS statistic, for instance, is used with the time-domain and has been applied to deal with signals from machining processes monitoring [22]. The RMS value x_{RMS} from a raw signal x is calculating by using Equation (4) [23].

$$x_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x^2(i)} \qquad (4)$$

Where N is the amount of discrete data of the signal x in a time interval.

Results obtained in previous researches about monitoring of the dressing process by using both AE and vibration signals, for example, and intelligent systems, such as ANN and Fuzzy systems, showed a satisfactory classification rate, but at high operating cost. Thus, the present work studies SHM systems, through time-domain analysis based on EMI method, widely used to look for cost reduction and a simplified methodology. Experimental procedures are described in the next section.

2. Material and methods

Experimental dressing tests were performed by using a conventional aluminum oxide grinding wheel model 38A150L6VH, from NORTON, with dimensions of 355,6 x 25,4 x 127 mm, mounted on a Sulmecânica model RAPH 1055 surface grinding machine. A single-point dresser of cut natural diamond was used for the dressing tests. The wear of the diamond was measured at intervals of 100 passes through pictures captured by using a digital microscope model DIGIMICRO 2.0 from DNT, with zoom in of 20x. The worn area of the diamond was measured by using CAD (computer aided design) software. Figure 2 presents the materials that were used in the experiment.

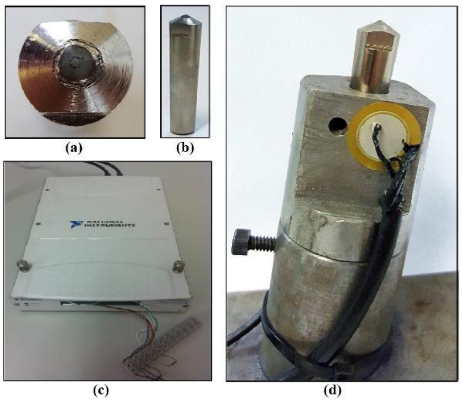


Fig. 2. Materials used in the test bench: (a) and (b) superior and side views of the single-point dresser of natural diamond, respectively; (c) Data acquisition system; (d) Dresser and PZT patch placed on the holder.

Dressing tests were conducted based on researches [1], [4] and the diamond was worn until its end life, that is, when it was observed its metallic base leaning against the grinding wheel surface and generating sparks. The dresser speed was kept constant at 3.45 mm/s, the depth of cut was 40 μm, and it was not used cutting fluid with the aim of causing a faster wear.

A low cost piezoelectric patch (PZT) was used as transducer, model 7BB-20-6, from MURATA, which was built with a circular bronze material of 20 x 0.20 mm (diameter x thickness), and a piezoelectric ceramic of 14 x 0.22 mm (diameter x thickness). As can be seen in Figure 2, the patch was fixed on the dresser holder, carried out by using a thin layer of cyanoacrylate glue. For the impedance measurement, the system proposed by [8] was adopted, which presented the circuit that was shown in Figure 1. The data acquisition system (DAQ) that was used for this work was model NI USB-6221 from National Instruments (Figure 2), which has sampling rate of 250 kS/s (kilosamples per second).

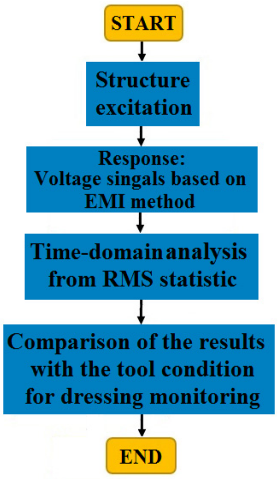


Fig. 3. Fluxograma do sistema proposto para o monitoramento da operação de dressagem

The transducer was excited through a resistor of 2.2 kΩ (R_S in Figure 1) by a chirp signal with magnitude of 1 V. The same signal was used for all measurements to guarantee the comparison. A mean of 3 repetitions for the impedance measurements were conducted to ensure a satisfactory accuracy. To detect the structural damages, impedance measurements were collected during an interval of 100 dressing passes, with the aim of identify changes in the mechanical impedance of the structure at different damage levels. Digital signal processing was performed by using MATLAB software on the electric voltage response collected from the time-domain. Feature extraction was conducted according to the steps presented in Figure 3.

To monitor temperature, a digital thermometer model MT455 from MINIPA was used, equipped with a thermocouple probe type K, which was fixed through a hole in the body of the dresser, close to the diamond. The temperature adopted as reference for every measurement was 30° C.

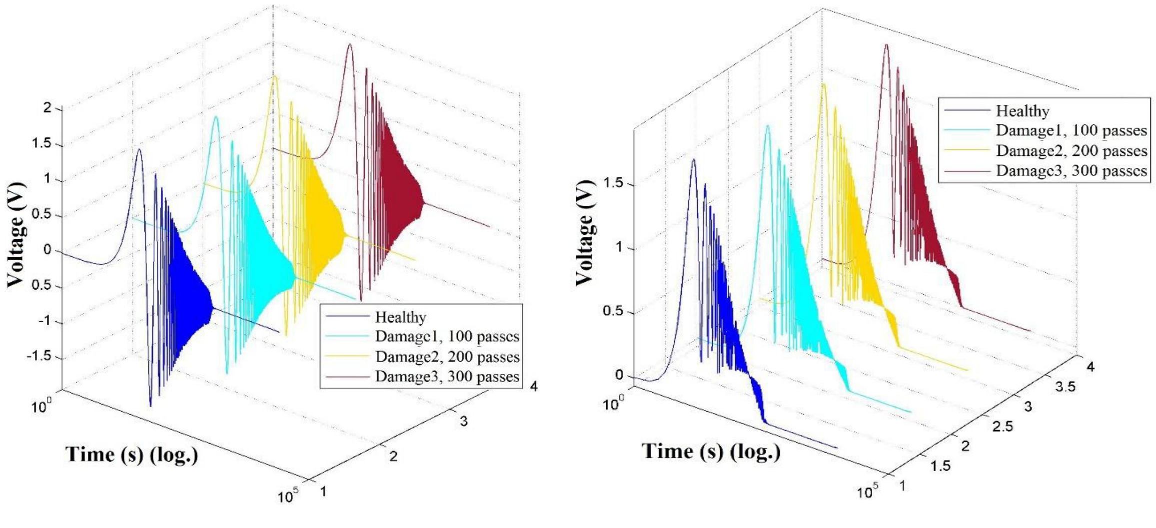
3. Results and discussion

Figure 4 presents the voltage signals responses read by the DAQ in the time-domain for each dresser diamond condition. The first measurement was recorded with the diamond integer, that is, with the tool new and before starting the dressing experimental tests (without wear). Throughout the test, measurements were collected for different damage levels, after 100 passes (damage 1), after 200 passes (damage 2) and 300 passes (damage 3). In Figure 4, it can be observed that voltage signals, which were not applied statistics yet, presented similar behavior among the three conditions in this study. The same happened when RMS was calculated for these signals, as presented in Figure 5. The signals presented similar behaviors showing a tendency over time, with some little variations. However, only a more thorough analysis could extract information about the process.

Figure 6 shows the pictures captured by the microscope in the side view of the dressers for the different wear levels caused in the dressing experimental tests. It can be observed the behavior of the diamond over all the test by means of three damage conditions: 100, 200 and 300 dressing passes, which were compared to the healthy diamond. As can be seen in Figure 6, as dressing process occurs, the diamond wears out up to its end of useful life, at 300 dressing passes. From the pictures taken by the microscope, by using CAD software, it was possible to calculate the diamond worn area over the dressing operation. It is possible to observe a tendency through linear interpolation, where the worn area proportionally increases according to the number of passes.

From the calculation of the statistics, such as the mean value of RMS signals previously showed in Figure 5, important information could be extracted about the dressing tool condition, as can be seen in Figure 6. These values were faced to the results of the dresser diamond wear, with the aim of a comparison, as well as to indirectly estimate a behavior pattern of the process, besides the monitoring system proposed in this paper. By observing the behavior of the RMS in Figure 6, it is possible to affirm that voltage signals calculated by RMS were effective to detect damages, because results showed a visible rising tendency of the magnitude as diamond wear occurs. The values could be fit by a straight line, which shows linear correlation of the voltage signals in time-domain and wear values observed in diamond through measurements of the worn area.

Therefore, it is possible to infer that signals in the time-domain clearly describe the behavior of the process, satisfactorily detecting damage levels of the diamond based on the images. In this way, the response signals in the time-domain calculated for RMS are appropriate to monitor the dressing process, because it was possible to estimate the diamond wear for different damage levels. From this study, a threshold could be defined before any damage occurs, ensuring a reliable dressing process.



(a) (b)

Fig.4. (a) Voltage signals in time-domain; (b) RMS of the signals in the time-domain

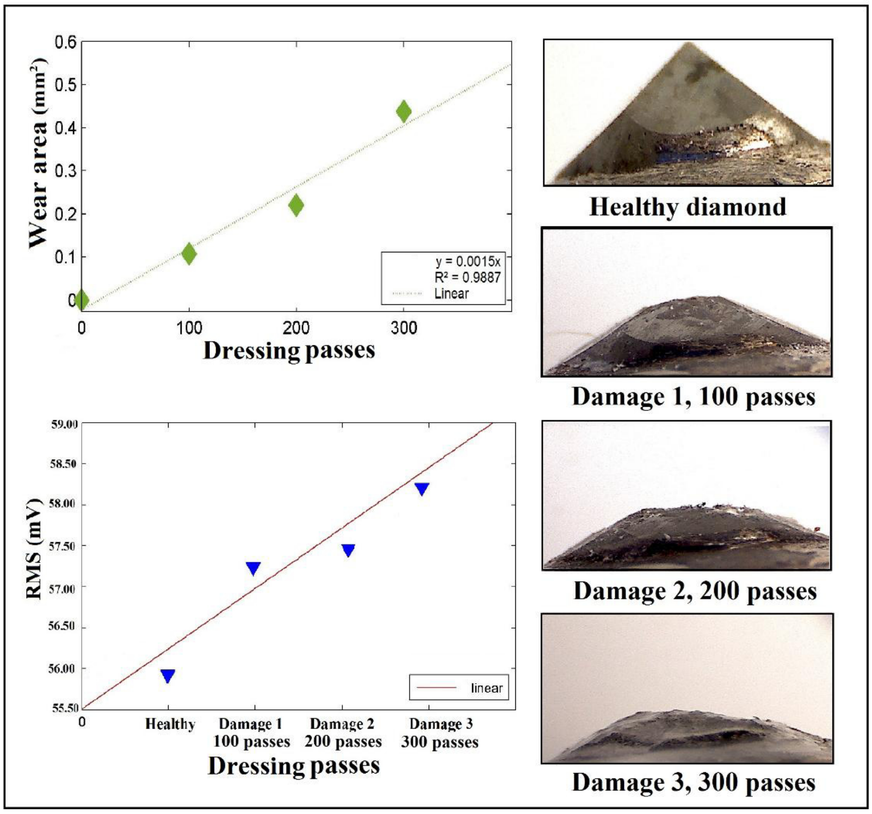


Fig. 6. Correlation between worn area of the dresser diamond and RMS of the voltage signals

4. Conclusion

This paper presented a new approach to monitor the dressing process from the time-domain analysis based on the EMI method, commonly used in SHM. By using a low cost piezoelectric transducer, of the type PZT, it was possible to detect damages that occurred in a natural diamond of a single-point dresser during experimental tests of the dressing process. By calculating the signals with the RMS statistic, it was possible to identify a behavior pattern, based on the magnitude of the signals, which clearly described the different damage levels of the diamond.

From this analysis, a magnitude threshold can be defined to avoid the diamond from suffering undesirable damages. That is useful to prevent that the dressing process continues working with a damaged dresser and, consequently, providing the correct roughness to the grinding wheel. Thus, a simple and economical system could be implemented by using this methodology, which would provide an optimized dressing operation and, accordingly, in the grinding operation.

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References

[1] P. O. C. Junior *et al.*, “Wear Monitoring of Single-Point Dresser in Dry Dressing Operation Based on Neural Models,” *Proc. IASTED Int. Conf. Model. Identif. Control (MIC 2017)*, vol. 36, no. Mic, pp. 178–185, 2017.

[2] A. T. Nguyen and D. L. Butler, “Correlation of grinding wheel topography and grinding performance: A study from a viewpoint of three-dimensional surface characterisation,” *J. Mater. Process. Technol.*, vol. 208, no. 1–3, pp. 14–23, 2008.

[3] P. R. Aguiar, A. G. O. Souza, E. C. Bianchi, R. R. Leite, and F. R. L. Dotto, “Monitoring the dressing operation in the grinding process,” *Int. J. Mach. Mach. Mater.*, vol. 5, no. 1, pp. 3–22, 2009.

[4] C. H. R. Martins, P. R. Aguiar, A. Frech, and E. C. Bianchi, “Tool Condition Monitoring of Single-Point Dresser Using Acoustic Emission and Neural Networks Models,” *IEEE Trans. Instrum. Meas.*, vol. 63, no. 3, pp. 667–679, Mar. 2014.

[5] D. Ai, H. Zhu, H. Luo, and J. Yang, “An effective electromechanical impedance technique for steel structural health monitoring,” *Constr. Build. Mater.*, vol. 73, pp. 97–104, 2014.

[6] T. Stepinski, T. . Uhl, and W. Staszewski, “Electromechanical impedance method. Advanced Structural Damage Detection: From Theory to Engineering Application,” *From Theory to Eng. Appl.*, no. 6, 2013.

[7] M. Rosiek, A. Martowicz, and T. Stepinski, “PZT based tunable Interdigital Transducer for Lamb waves based NDT and SHM,” *Mech. Syst. Signal Process.*, vol. 78, pp. 71–83, 2016.

[8] F. G. Baptista and J. F. Vieira, "A new impedance measurement system for PZT based structural health monitoring," *IEEE Trans. Instrum. Meas*, vol. 58, no. 3602–8, 2009.

[9] V. Augusto, D. De Almeida, F. G. Baptista, and P. R. De Aguiar, "Piezoelectric Transducers Assessed by the Pencil Lead Break for Impedance-Based Structural Health Monitoring," *IEEE Sens. J.*, vol. 15, no. 2, pp. 693–702, 2015.

[10] M. Marchi, F. G. Baptista, P. R. de Aguiar, and E. C. Bianchi, "Grinding process monitoring based on electromechanical impedance measurements," *Meas. Sci. Technol.*, vol. 26, no. 4, p. 45601, 2015.

[11] E. Silva, D. Freitas, and F. Guimarães, "Experimental analysis of the feasibility of low-cost piezoelectric diaphragms in impedance-based SHM applications," *Sensors Actuators A. Phys.*, vol. 238, pp. 220–228, 2016.

[12] R. Z. Silveira, L. M. Campeiro, and F. G. Baptista, "Performance of three transducer mounting methods in impedance-based structural health monitoring applications," *J. Intell. Mater. Syst. Struct.*, vol. 1, no. 14, 2017.

[13] P. Cawley, *The impedance method of non-destructive inspection*, 17th ed. 1984.

[14] R. Dugnani, "Dynamic Behavior o f Structure- mounted Disk-shape Piezoelectric Sensors Including the Adhesive Layer," *J. Intell. Mater. Syst. Struct.*, vol. 20, no. 13, pp. 1553 – 1564, 2009.

[15] İ. Asiltürk, M. Tinkir, H. El Monuayri, and L. Çelik, "An intelligent system approach for surface roughness and vibrations prediction in cylindrical grinding," *Int. J. Comput. Integr. Manuf.*, vol. 25, no. 8, pp. 750–759, Aug. 2012.

[16] D. M. S. Ribeiro, P. O. Conceição jr, R. D. Sodário, M. Marchi, P. R. Aguiar, and E. C. Bianchi, "Low-Cost Piezoelectric transducer applied to workpiece surface monitoring in grinding process," *ABCM Int. Congr. Mech. Eng. - COBEM*, vol. 23, no. 1–10, 2015.

[17] O. Bilgen, Y. Wang, and D. J. Inman, "Electromechanical comparison of cantilevered beams with multifunctional piezoceramic devices," *Mech. Syst. Signal Process.*, vol. 27, pp. 763–777, 2012.

[18] M. A. De Oliveira, J. V. Filho, V. L. Junior, and D. J. Inman, "A novel time-domain technique for damage detection applied to SHM using Savitzky-Golay filter," *Aerosp. Eng. A Roadmap to Intell. Struct. - Proc. 9th Int. Work. Struct. Heal. Monit. IWSHM*, vol. 1, pp. 996–1003, 2013.

[19] Y. Q. Ni, X. G. Hua, K. Q. Fan, and J. M. Ko, "Correlating modal properties with temperature using long-term monitoring data and support vector machine technique," *Eng. Struct.*, vol. 27, pp. 1762–1773, 2005.

[20] F. G. Baptista, D. Budoya, V. A. D. Almeida, and J. A. C. Ulson, "An experimental study on the effect of temperature on piezoelectric sensors for impedance-based structural health monitoring," *Sensors*, vol. 14, no. 1208–27, 2014.

[21] D. M. D'Addona, D. Matarazzo, P. R. de Aguiar, E. C. Bianchi, and C. H. R. Martins, "Neural Networks Tool Condition Monitoring in Single-point Dressing Operations," *Procedia CIRP*, vol. 41, pp. 431–436, 2016.

[22] N. Tandon and A. Choudhury, "A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings," vol. 32, no. 1999, pp. 469–480, 2000.

[23] J. W. Nilsson and S. A. Riedel, *Circuitos Elétricos*. 2003.