Probabilistic Approach for Electromechanical Impedance-Based SHM Models

Abordagem Probabilística de Modelos de SHM baseados em Impedância Eletromecânica

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ABSTRACT
Applying structural health monitoring techniques has become very important in engineering and aeronautics. The technique based on electromechanical impedance is one of them. In this work, the electromechanical impedance-based SHM technique is applied...
to determine the existence of damage in an aluminum beam using the Root Square Deviation (RMSD) damage metric. Furthermore, this contribution aims to apply the concept of stochastic evaluation in the context of the electromechanical impedance-based SHM technique by using the Monte Carlo method to generate random numbers. The development of the work is to validate two models, one with the impedance signals and the other stochastically, and thus build the linear regression model for both. In the end, the results are compared to test the representation of the failure identification in the beam.

**Keywords:** structural health monitoring, damage detection, monte carlo method, stochastic models.

**1 INTRODUCTION**

Structural Health Monitoring (SHM) implements a failure detection strategy that assesses and ensures infrastructure integrity in aerospace, civil, and mechanical engineering. It is an emerging technology that leads to developing systems capable of continuously monitoring structural damage with minimal human intervention (KESSLER et al., 2002).

One of the main techniques of SHM is the electromechanical impedance-based monitoring method, which requires the structure to be excited in an appropriate frequency range using piezoelectric transducers (PZT) that are either glued or embedded in the structure. They undergo some deformation when excited at high frequency and produce an electric field. Thus, they can be used as sensors to monitor the system's response to
environmental disturbances and as actuators acting on the structure to provide the appropriate behavior (DURVAL et al., 2018; FREITAS et al., 2021; MAIO, 2011; MOURA JR, 2008; OLIVEIRA, 2013; PALOMINO, 2008; PALOMINO et al., 2011; PALOMINO et al., 2012; PARK et al., 2005; REZENDE et al., 2023).

According to Park et al. (2003), the technique uses the dielectric property of PZT materials, forming a non-destructive evaluation method, as it does not affect the structure's characteristics. According to Moura Jr (2008), the structural health monitoring method uses electromechanical impedance signatures obtained by a sensor to monitor incipient failures.

The most commonly used sensors/actuators are piezoelectric transducers, which are fixed to the structure so that they do not interfere with its behavior (MOURA JR, 2008). These sensors/actuators monitor the structure’s stiffness, damping, and mass changes. The impedance sensor consists of a small piezoelectric patch, usually less than 25x25x1mm, which directly measures the local dynamic response (PALOMINO, 2008). The PZT patches use a very low voltage difference, generally less than 1V, thus generating high excitation frequencies at a specific location on the structure (RAJU, 1997; PARK et al., 2003).

When using piezoelectric elements, there are advantages and disadvantages. The main benefits are relative insensitivity to temperature, linear responses at low excitation levels, low weight, the possibility of exhibiting wideband frequency responses, and the great flexibility to be used as sensors and actuators. On the other hand, the main disadvantages are difficulty cutting to shape PZT patches due to their ceramic characteristics, hysteresis in high electric fields, and decay of the polarization characteristics of the piezoelectric elements, thereby reducing their performance (MOURA JR, 2008).

The process for obtaining impedance signals simultaneously uses direct and inverse effects of PZT patches, which requires applying a high excitation frequency potential difference to get a dynamic response from the structure for signal acquisition. This dynamic response from the structure represents only the local area where the PZT patch is located, which is then collected by the sensor and converted to an electric current.
signal. Thus, when a mechanical failure occurs in the structure, the dynamic response changes (given by the impedance signal) and, consequently, in the electrical response of the PZT patches (PARK, INMAN, 2005; PALOMINO, 2008).

Figure 1 presents an example for better visualization of the process of monitoring electromechanical impedance (MOURA JR, 2008).

Figure 1 - One-dimensional model of the electromechanical impedance monitoring process.

![One-dimensional model of the electromechanical impedance monitoring process.](image)

The electromechanical impedance can be expressed as a function of the voltage applied to the PZT patch and the resulting current obtained due to the system’s dynamic response. The admittance equation relates the electrical impedance given by the patch to the mechanical impedance of the structure presented by Eq. 1 (LIANG et al., 1994).

\[
Y(\omega) = \frac{I}{V} = i\omega a \left( \varepsilon_{33}^{T} - \frac{Z(\omega)}{Z(\omega) + z_a(\omega) d_{3x}^2 Y_{xx}^E} \right)
\]

(1)

where \(Y(\omega)\) is the electrical admittance, \(V\) is the input voltage to the actuator, \(I\) is the output current of the PZT patch, \(a\) is the geometric constant, \(d_{3x}\) is the piezoelectric coupling constant, \(Y_{xx}^E\) is Young's modulus, and \(\varepsilon_{33}^{T}\) is the complex dielectric constant of the PZT patch at zero stress, \(Z_a(\omega)\) is the mechanical impedance of the PZT patch, and \(Z(\omega)\) is the mechanical impedance of the structure.

According to Sun et al. (1995), impedance response graphs provide qualitative information on the structural integrity of the area under study, regarding the damaged and undamaged areas. Quantitative data is usually provided through a scale known as the damage metric. According to Palomino (2008), damage metrics are statistical techniques that can better evaluate the measurement performed by the electromechanical impedance
method. This method considers the change between measurements, considering the pristine structure as a reference. This way, comparisons between the response of the undamaged and damaged structures can be measured.

The damage metric used in this work was initially developed by Sun et al. (1995) and is described as the Root Mean Square Deviation (RMSD), as shown in Equation 2.

$$M = \sum_{i=1}^{n} \sqrt{\frac{(\text{Re}(z_{i,1}) - \text{Re}(z_{i,2}))^2}{\text{Re}(z_{i,1})^2}}$$

where $M$ is the damage metric calculated, $Z_{i,1}$ is the measured signal of the undamaged structure and $Z_{i,2}$ is the measured signal of the damaged structure in the frequency range $i$, and $n$ represents the number of frequencies evaluated in the defined range (BITTENCOURT; STEFFEN JUNIOR, 2010). The higher the value presented by the damage metric, the more significant the difference between the signals of the structure with and without failure.

In the realm of Structural Health Monitoring (SHM) using electromechanical impedance, determinism is elusive. The variables involved are known and stochastic, with some input variables being unknown, leading to significant uncertainty. In such scenarios, the Monte Carlo method is often employed to address the complexity and randomness inherent in the system.

The Monte Carlo method transforms a set of random numbers into another set of numbers (random variables) with the same distribution as the variable being considered (PRADO, 2009).

As per Lustosa et al. (2004), the Monte Carlo simulation is a technique that employs random number generation to assign values to system variables being studied. Random numbers can be obtained from various sources, such as tables, roulette wheels, raffles, or software using specific functions. These numbers are drawn from deterministic variables, where the outcome is defined by experiment conditions, and probabilistic variables, which introduce random effects based on probability distributions. The
simulation iterates through each scenario, and the results are stored. Upon completion of all repetitions, the generated results are transformed into a frequency distribution, allowing for the calculation of descriptive statistics such as mean (expected value), minimum value, maximum value, and standard deviation.

Additionally, the simulation executor can design future operating scenarios for the analyzed system. Thus, the average of an iteration can be established as a number that describes several other values and concentrates the distribution data. On the other hand, the standard deviation shows the degree of dispersion existing about the average of an iteration; that is, the closer to zero the standard deviation is, the closer the data is to the mean; otherwise, it indicates being spread over a range of values (LUSTOSA; PONTE; DOMINAS, 2004).

Moore and Westherford (2005) emphasize that the Monte Carlo method is one of several methods for analyzing uncertainty propagation. Its great benefit is determining how a known random variation, or error, affects the performance or feasibility of the system being modeled.

The Monte Carlo simulation method can be applied to decision-making problems involving risk and uncertainty, i.e., situations where the performance of the variables involved with the problem is not deterministic (LAW and KELTON, 1991). Given that SHM has potential applications in various areas and high-cost structures, a study with a stochastic approach would make its use even more feasible.

Hence, the purpose of this contribution is to provide an investigation into the experimentation and validation of stochastic models used for predicting mechanical failures.

2 METHODOLOGY

The experimental procedure involved conducting electromechanical impedance measurements by coupling PZT to an aluminum beam under three conditions. The first condition served as the baseline, where the beam was intact. In the other two states, simulated damages in added mass (magnet) were introduced, with one damage in each condition. The structure used was an aluminum beam with dimensions of 300x25x3 mm,
as shown in Fig. 2a. The simulated damage was based on adding mass to the system glued to the structure with double-sided tape in two different positions. A magnet made the mass for the case studied with dimensions of 10x10x10mm. The adopted location for the damage experiment was 7 cm relative to the first and second damage, as shown in Fig. 2b and 2c. For each damage, individual data was collected, and it is also possible to observe that the piezoelectric sensor/actuator is fixed to the beam.

Figure 2 - Aluminum beam with PZT patch used in the experiment.

![Figure 2](image)  

The acquisition system was based on an impedance monitoring board from HP, the PmodIA. This equipment provides users with a way to measure electromechanical impedance. It uses the AD5933 IC, which has an integrated frequency generator of up to 16,776 MHz and a digital converter (ADC) to excite an unknown external impedance at a known frequency. This available frequency is sent through one of the SMA connectors. The other SMA connector captures the frequency response and is forwarded to the ADC. Finally, a Discrete Fourier Transform (DFT) is performed on the sampled data, storing the real and imaginary parts of the solution in the chip’s data registers (DIGILENT, 2016).

When communicating with PmodIA through the I2C interface, users can program PmodIA to perform a scan on a circuit to obtain the electromechanical impedance. Figure 3 shows the impedance converter in question.
Figure 3 - PmodIA Impedance Converter (DEVICES, 2013).

Source: authors.

Figure 4 shows the signature acquisition system, where the PZT patch of the aluminum plate is connected to the PmodIA board, and then the board is connected to the computer.

Figure 4 - Impedance signal acquisition diagram.

Source: authors.

The PmodIA board, once assembled with the aluminum beam, communicates with a computer through a USB connection, and impedance signal measurement is performed using the AD5933 software. This signal acquisition interface, as illustrated in Figure 5, consists of a frequency generator of up to 16 MHz, a direct digital synthesis (DDS) 27-bit sine wave alternating voltage generator, a digital-to-analog converter (DAC), and a programmable gain amplifier (PGA1). The signal reception stage consists of a current-to-voltage converter (CVC), another gain amplifier (PGA2), and a low-pass filter. The data is then processed by a 12-bit analog-to-digital converter (ADC) and a mechanism that performs a Discrete Fourier Transform (DFT) with 1024 points in a multiple accumulation window (MAC). As a result, from an unknown impedance Z, the IC returns the real and imaginary parts of the (DFT). Communication is performed via the I2C protocol (DEVICES, 2013).
The frequency range used in this experiment was from 60 kHz to 70.2 kHz, with a sampling of 511 points for analysis. Thirty electromechanical impedance signatures were collected for each level (baseline, damage #1, damage #2), totaling 90 samples.

Initially, with the impedance measurements, a Matlab® program was developed from a set of 30 samples, performed the average of each level, and then, to quantify the damages, the damage metric was applied, according to Equation 2. Subsequently, five samples from each group were separated from the 30 samples, totaling 15, to build a linear regression model with the remaining samples (75 samples).

For the stochastic component, the mean and standard deviation of the metric results for each level were calculated. Then, ten random numbers were generated for each group, and a regression model was built to validate the model and compare it with the previous regression.

3 RESULTS AND DISCUSSIONS

Data acquisition of 30 samples for each level of damage was gathered. From the data, it is possible to notice a little difference due to impedance variation between the baseline and the damages, as shown in Figure 6.
This variation can demonstrate the presence of damage visually on the aluminum beam. However, it is necessary to apply a statistical method that quantifies this damage. The RMSD metric was used to quantify the damage in the dataset, as shown in Figure 7.

One can notice that the technique used could determine the presence of damage in the beam while demonstrating the efficiency of the EMI-based SHM methodology. Figure 8 shows the average of the baseline and the two damages.
From the calculation of metrics, linear regression is built to validate the model, where linear regression estimates the values of one variable based on the known values of another. The term "linear" refers to the highest first-degree term that defines the relationship between two variables.

For the development of this work, five samples are taken from each level, and then linear regression is performed with the remaining samples, as shown in Figure 9.

Figure 8 – Mean of Baseline and Damage measurements.

Figure 9 – Linear regression with 75 measurements.
In Figure 9, the red line is the linear regression, and the blue dots are the levels (baseline, damage #1, and damage #2). For the model to be validated, the various points must find the line that best approximates them. As seen, the model is validated because the points are close to the line; thus, the validated model represents the identification of failure in the beam.

For the construction of the Monte Carlo method, which is the stochastic part, the mean and standard deviation of the metric for each level are required. The baseline mean is 0.0754, damage #1 is 0.3502, and damage #2 is 0.5017. The standard deviation of the baseline is 0.0236, damage #1 is 0.1066, and damage #2 is 0.0657. After calculating the mean and standard deviation, ten random numbers are generated for each level, totaling 30 random samples. Based on these 30 samples, the regression model is created. Figure 10 shows the linear regression of the stochastic part.

As seen in Figure 10, the points of each level are close to the line; thus, the regression model is validated and presents the damage in the beam.
Given the two scenarios of linear regression (with 75 signals and with random data), it is observed that both regressions present similar points, thus showing that there is damage in the beam.

4 CONCLUSIONS

This contribution presented the application of the electromechanical impedance-based SHM technique, which aimed to introduce the stochastic concept in identifying a fault in the beam. The objective was achieved by presenting two linear regression models to validate the fault identification, and both models showed similar results, representing the fault in the beam.

Therefore, future work is intended to be carried out using the Monte Carlo method in other types of structures to develop more robust damage assessment models, also reducing the amount of data to be stored.
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