Piezo-actuated device for a bio-structural monitoring application through vibration-based condition and electromechanical impedance measurements

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Abstract. This study presents a numerical and experimental development of a piezo-actuated device used for monitoring the stiffness variations of its support through electromechanical impedance measurements. The piezo-device and its components define a clamped beam system activated dynamically by two piezo-transducers that transmit vibrations to the support (monitoring substrate). An harmonic finite element analysis was carried out to understand the effects of the substrate properties on the dynamics of the piezo-device. Experimental tests corroborated the simulations with the correspondence of modal shapes and frequency response functions (FRFs) when the substrate varies its stiffness. A biomedical application was conducted in a bone specimen with three embedded teeth to monitor the stiffness variations induced by drillings in the bone. Results showed that the bone stiffness monitoring could be possible through the teeth due to that the drillings effect were quantified by electrical impedance signals.

1. Introduction
Structural health monitoring (SHM) techniques have been applied in several practical approaches during the last few years; the majority focused on evaluating structural damages [1-4]. The understanding of structural behaviour is a requirement for the application of SHM methodologies in operating conditions [5,6]. Methods based on vibrations deal with the determination of changes in the modal properties, these changes are caused by damages that modify the structural condition. Non-destructive identification techniques can be classified into two categories: those focused on local damage and others in the global dynamic behaviour [7]. Local identification methods are applied on the basis of non-destructive evaluation tools such as visual inspections, acoustic emission, ultrasound, magnetic particle inspection, radiography and Foucault currents, among others [8-10]. The majority of tools requires the previous location of the diagnosis area to proceed to an inspection. However, methods based on the global vibration show to be an alternative that overcomes those limitations as evidenced by different studies [11-16]. The application principle is supported on the basis of the structural dynamics which is governed by the following physical properties; mass, damping, and stiffness. Variations of these properties will cause modifications in the dynamics; it means that modal properties are altered. Recent studies have
explored the application of SHM in the biomedical field through the EMI technique; for example, biomedical sensors to monitor the bone condition [17,18] or the assessment of dental implants [19,20].

This paper presents a numerical and experimental analysis of a piezo-actuated device used to monitor the structural changes of its support by means of mechanical vibrations. The study shows how the elastic variations of the support modify the vibration conditions and how these modifications can be quantified with the electrical impedance. An application is shown with teeth embedded in a bone sample, in which rigidity variation due to drillings done on the sample are quantified with the electrical impedance measurements taken in the piezo-device.

2. Materials and methods

2.1. Finite element analysis for the piezo-actuated system

This section describes a harmonic finite element analysis (FEA) in order to obtain the frequency response functions that characterize the dynamic behavior of a piezo-actuated system. Figure 1(a) illustrates a piezo-device attached to a coupling interface and a supporting substrate. On this system, a parametric analysis is carried out to observe the effects on the vibratory states (kinematic changes) when the elastic properties of the substrate are varied as well as the coupling interface type (cone or tooth).

![Figure 1. Finite element models and boundary conditions.](image)

For the FEA simulations, the physical and mechanical properties are listed in table 1.

| Part          | Material       | Young’s modulus [GPa] | Poisson ratio | Density [kg/m^3] |
|---------------|----------------|-----------------------|---------------|------------------|
| Orthodontic Wire | Aluminum      | 177                   | 0.31          | 7750             |
| Mass          | Aluminum      | 70                    | 0.33          | 2700             |
| Piezo-sheets  | PZT-5H        | Anisotropic (equation(1)) | -     | 7800             |
| Substrate     | Copper alloy  | 127                   | 0.34          | 8670             |
| Tooth         | Aluminum      | 100                   | 0.3           | 2500             |

All materials were considered isotropic linear elastic except for the piezo-sheets that was assumed anisotropic according to the following material properties: \( C_{11} = 126 \text{ GPa}, C_{12} = 84.1 \text{ GPa}, C_{13} = 84.1 \text{ GPa}, C_{21} = 84.1 \text{ GPa}, C_{22} = 126 \text{ GPa}, C_{23} = 79.5 \text{ GPa}, C_{31} = 84.1 \text{ GPa}, C_{32} = 79.5 \text{ GPa}, C_{33} = 126 \text{ GPa}, C_{44} = 23 \text{ GPa}, C_{55} = 23 \text{ GPa}, C_{66} = 23 \text{ GPa}. \) Poling direction was defined at \( z \)-direction. For the activation of the piezo-device, a harmonic distributed force \( P \) was applied in the frequency range of 1-50 kHz as described in figure 1(b). It is noted that both forces are applied synchronously but in
opposite directions so that one sheet remains in compression and the another in tension. The forces were applied with the same magnitude, and it was estimated with the electromechanical models reported by [21]. Boundary conditions were defined in the following way: fixed support in the cable (beam) in the first part of it; rigid contact surfaces were established between the interfaces that couple the substrate and the device. This condition was created in order to guarantee the movements between the bodies. Therefore, there are not permitted relative displacements between interfaces that interact in the model. Additionally, fixed support conditions were applied on the faces A and B of the substrate. Rectangular elements (piezoelectric sheets, brass plates, cable) and triangular elements (concentrated mass) were chosen for meshing, as seen in figure 1.

2.2. Experimental setup for the velocity measurements

![Experimental setup diagram](image)

**Figure 2.** Velocity measurements of the piezo-actuated system with different substrates (Aluminum, Bronze and Steel).

An experimental setup was designed to velocity measures in the piezo-system evaluated through simulations. Therefore, a computer, a data acquisition card (NI DAQ 6211), a high voltage amplifier 2205 (TREK Inc., Lockport, NY, USA) and a laser vibrometer POLYTEC CLV-2534 (Polytec Inc., Auburn, MA, USA) are necessary elements for this purpose. The configuration of this experiment can be seen in figure 2. Velocity measurements were taken in the piezo-device for different metallic substrates (aluminum 70 GPa, Bronze 120 GPa and Steel 200 GPa, according to the local material supplier) coupled to a connection interface (aluminum cone). The measurement points were defined in the following way: 8 points on the electric piezo-sheet, 2 points on the wire and 2 points on the mass; locations are marked in figure 1. An epoxy adhesive was used to bond all interacting parts of the system. The piezo sheets were connected to the output of the voltage amplifier, in which a 35 V excitation signal was applied. A frequency sweep was imposed from 0 to 20 kHz in 1s with a sampling frequency established in 100 kHz. The substrates were bonded at the bottom surface in a rigid table for avoiding non-desired motions.
2.3. Electromechanical impedance measurements in metallic substrates and a bone sample

In figure 3(a) is shown a first experimental setup settled with the aim to measure the electrical impedance of the piezo-device coupled to the same metallic substrates described in section 3.2. The substrate dimensions are depicted in figure 1. The aim of this test is to simulate Young’s modulus variation in the substrate. An impedance analyzer (E4990A, Agilent, Palo Alto, CA) was configured with a sweep signal setup between 0-20 kHz with 1601 resolution points. For the context of a bio-structural application, a second experimental setup was set to perform impedance measurements in cancellous bone samples of cleaned cow hip bone obtained from a local butchery. The sample consists of a cancellous bone prismatic specimen with three embedded teeth that emulate the human maxillary bone-teeth system. Maxillary bone cavities were manufactured by mechanical drillings. All teeth were integrated with a commercial silicone layer that represents an artificial periodontal ligament as depicted in figure 3(b).

Figure 3. Electromechanical impedance measurements. (a) Variations of the metallic substrates. (b) Stiffness variation in a bone sample.

Dimensions of the sample are $36.9\text{mm} \times 27\text{mm} \times 18.4\text{mm}$ that correspond to length $\times$ height $\times$ width. In order to study the bio-monitoring, damage conditions were induced by a sequence of mechanical drillings of $2.5\text{mm}$ (diameter). The drilling order is described by colors in figure 3(b). Electrical resistance measurements were acquired with the same configuration of the first experiment. EMI technique consists of exciting both piezo-transducers by a harmonic voltage and obtaining the current that passes through these simultaneously; the details of the method were reported by [16].

3. Results

3.1. Finite element analysis results: Effects of the elastic variations of the substrate on the kinematic of the piezo-device

In this section, the results of the finite element analysis (FEM) are described in order to analyze the dynamic behavior of the complete system shown in figure 1. The mean velocities for the points corresponding to the piezoelectric sheets (demarked in figure 1) and the mass are shown in figures 4(a) and 4(b). The blue highlighted line corresponds to the velocities when the canine tooth acts as the interface of the piezo-device, and the red line, when it is coupled to the aluminum cone. In both figures, the black line represents the velocities of the clamped piezo-device; it means that there is no substrate and no coupling interface. In figure 4(a), in the interval of 1-10 kHz is analyzed that the coupling interface has no effect on the kinematics of the piezo sheet since basically the signals present the same trending. But from 10 kHz and beyond, it is corroborated that the piezo sheets vibrate in different ways when the interface is changed. The resonance peaks are numbered to point out the effects of each interface (tooth and cone). It is observed that the resonances 1 and 2 present the same values of frequency for both interfaces. The relationships between resonances 3, 4, 5, and 6 are affected by the changes in
mass and stiffness introduced by the interfaces in the kinematics of the device. In figure 4(b) is seen that
the velocities of the mass are higher when the cone acts as a coupling interface; it can be associated with
the mobility that permits the tooth inside the substrate. This can be easily verified with the amplitudes
of the velocity shown in figure 4(b).

![Figure 4](image1)

**Figure 4.** Mean velocities in the piezo-device with a substrate of Young’s modulus 5 GPa. (a) Piezoelectric sheet. (b) Mass.

Young’s modulus variations (substrate) were considered as a correlation parameter to observe the
effects generated in the dynamics of the system (piezoelectric sheets, interface, and substrate). The
following elastic moduli were assigned to the substrate, 5 GPa, 10 GPa, 15 GPa, and 20 GPa. The results
of the mean velocities for each interface are illustrated in figure 5. There is observed that the piezo-
device can detect the elastic variations of the substrate in the velocity magnitudes of the piezo-sheets,
which reflect a higher sensitivity to the variations in 33180 Hz (cone) and 30402 Hz (tooth).

![Figure 5](image2)

**Figure 5.** Mean velocities in the piezo-sheet. (a) Cone comparison. (b) Canine tooth comparison.

The characteristic peaks show that the signal conserves the structure; however, there is a shift of the
signal to the left when the modulus of elasticity is increased. It means that the vibration condition is
modified when the substrate change its elastic properties. With the vibration mode is demonstrated that
the vibratory condition is the same independently of coupling interface as illustrated in figure 5; but it
is altered by the elastic variations of the substrate. The compared modes were determined for a substrate
of 10 GPa.
3.2. Experimental results: Effects of the elastic variations of the substrate on electro-mechanical conditions of the piezo-device

In figure 6(a) are observed the mean velocities (time-domain) taken in the piezo-sheet (red points marked) and transformed to the frequency spectrum with Fast Fourier Transform (FFT). These velocities correspond to three different substrates (Aluminum 70 GPa, Bronze 120 GPa, and steel 200 GPa) used with the aim to verify the vibration condition when the substrates are changed. Two regions of interest that show sensitivity to the elasticity changes of the substrate were observed; these are delimited in between 0-100 Hz and 3-11 kHz. In these zones, it is verifiable as the slopes increased its value when Young’s modulus augmented. Particularly, the section A-A is pointed out since a sensitive resonance peak at 9406 Hz is evidenced. This region was extended in figure 6(b) and the vibration mode of the piezo-sheet was reconstructed (using nine measurement points) for the test with the aluminum substrate. The determined vibration shape can be compared with the vibration mode obtained with FEA, which is shown in figure 5. The comparison illustrates that the piezo-sheet is deformed by the vibratory condition del piezo-device which depends on the properties of the substrate. According to the results, the effects of the velocity changes are reflected in the electrical properties of the piezo-sheets, as shown in figure 6(b).

![Figure 6](image_url)

**Figure 6.** (a) Mean velocity of the piezoelectric sheet in the frequency spectrum. (b) Electrical resistance of the piezoelectric sheet.

In order to determine a correlation between the electromechanical behavior of the piezo-device, the electrical resistance was measured through an impedance analyzer with the experiment described in section 3.3. The frequency range in between 8 to 15 kHz (figure 6(b)) is compared with the obtained velocity measurements in the same interval. There are identified two main peaks in the electrical resistance; first peak at 9 kHz and a second peak at 11.5 kHz, it is evident that the electrical peaks present a correlation with the kinematic ones since the resonances identified in the velocity functions describe the same values in the frequency. The results demonstrate that electrical resonances come strictly from the vibration mode of the piezo-device.

3.3. Bone monitoring through electromechanical impedance measurements

In this section the results of an application of bio-monitoring are presented according to the proposed experiment in section 3.3, detailed in figure 3(b). Damage locations were defined in the bone sample with the objective to evaluate the damage from the neighbour teeth through electromechanical impedance measurements. In this test, it is considered that a human tooth can be used as a probe since it is naturally coupled to biological structures such as the case of maxillary bone. Bone changes its
structural properties by factors like; force application, natural remodelling process and metabolic deceases. The aim is to demonstrate the usefulness of the piezo-device for detecting variations in mechanical parameters of bio-structures.

Figures 7(a) and 7(b) show the electrical resistances measured for the bone sample from a molar and premolar tooth, both located in the same specimen. Analyzing the curves, one observability window was chosen between 9-10.5 kHz (first peak at 9.6 kHz) where all resistance signals presented sensitivity to the induced damages showing differences in the maximum amplitudes. For the molar tooth, it was observed that the damage 1 shifts downwards from the pristine signal and then these shift upwards until the third damage. For the premolar tooth is evidenced the same trend. These pertubartions evidenced that the damage can be monitored from the tooth and these changes can be quantified through statistical indexes.

![Figure 7](image)

Figure 7. Electrical resistance signals measured in the bone sample. (a) Acquired resistance signals with the molar tooth. (b) Acquired resistance signals with the premolar tooth.

4. Conclusions
Numerical and experimental evaluation of the system showed the effects of the elastic variations in the substrate on the vibration condition of the piezo-device. The application of the electromechanical impedance technique (EMI) verified that the resonances in the frequency corresponded with the mechanical resonances of the system. Two intervals were identified between 0-100 Hz, and 3-11 kHz where the device presented a higher sensitivity to the elastic changes of the substrate. This result leads to conclude that the designed device can be used as a structural monitoring instrument since it presents the ability to capture the elastic changes in its vibratory condition.

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