3D-printed smart structures for dynamic measurement

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My doctoral research focuses on using **3D printing** technology to create **smart structures** capable of dynamic measurements. Additive manufacturing and advanced materials provide innovative solutions to enable their development for engineering applications. The research findings have potential applications in industries such as aerospace, automotive and bioengineering (Figure 1). The project aims to develop a general procedure for creating 3D printed smart structures that ensure high sensor performance under stress, reliability and structural strength.

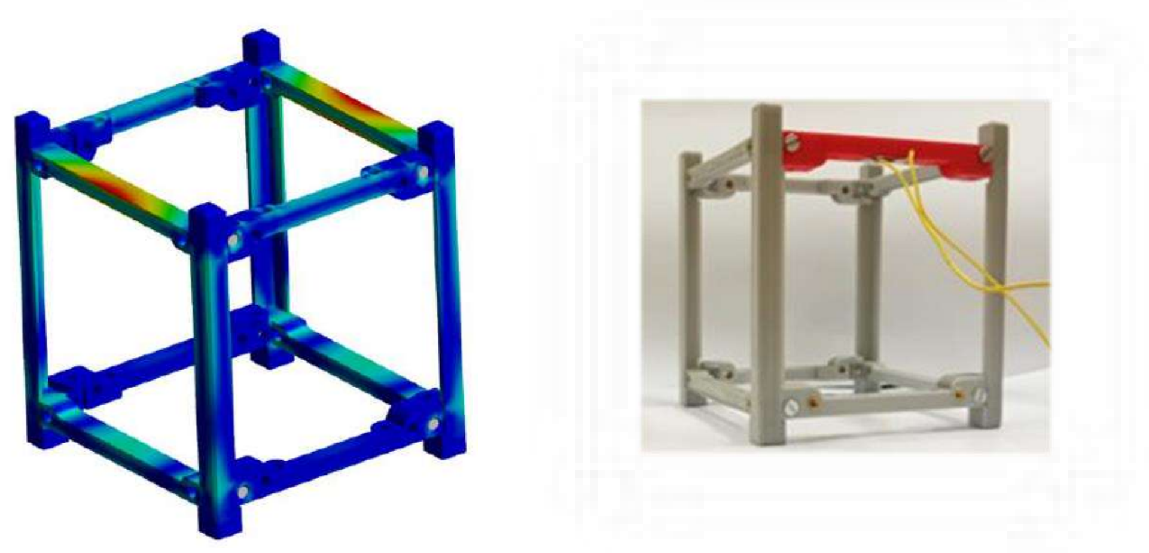

Figure 1 -Examples of possible sensors integrated into CubeSat for space applications and FEM model of the smart-structure

Introduction

The revolution brought by Additive Manufacturing technology has opened the way to new possibilities and design concepts, thanks to its ability to create objects with complex geometries and the integration of different materials during the process. The unique feature of Fused Deposition Modeling (FDM) technology, which deposits material layer by layer, allows precise control of the single-layer process (Figure 2); in fact, the method offers the advantage of incorporating different materials in specific points of the structure during manufacturing and represents the turning point for the creation of integrated sensors. In fact, these play a fundamental role in structural monitoring, which involves the analysis of physical quantities measured directly on the structure under investigation to detect any changes in structural behavior and identify potential premature or unexpected failures.

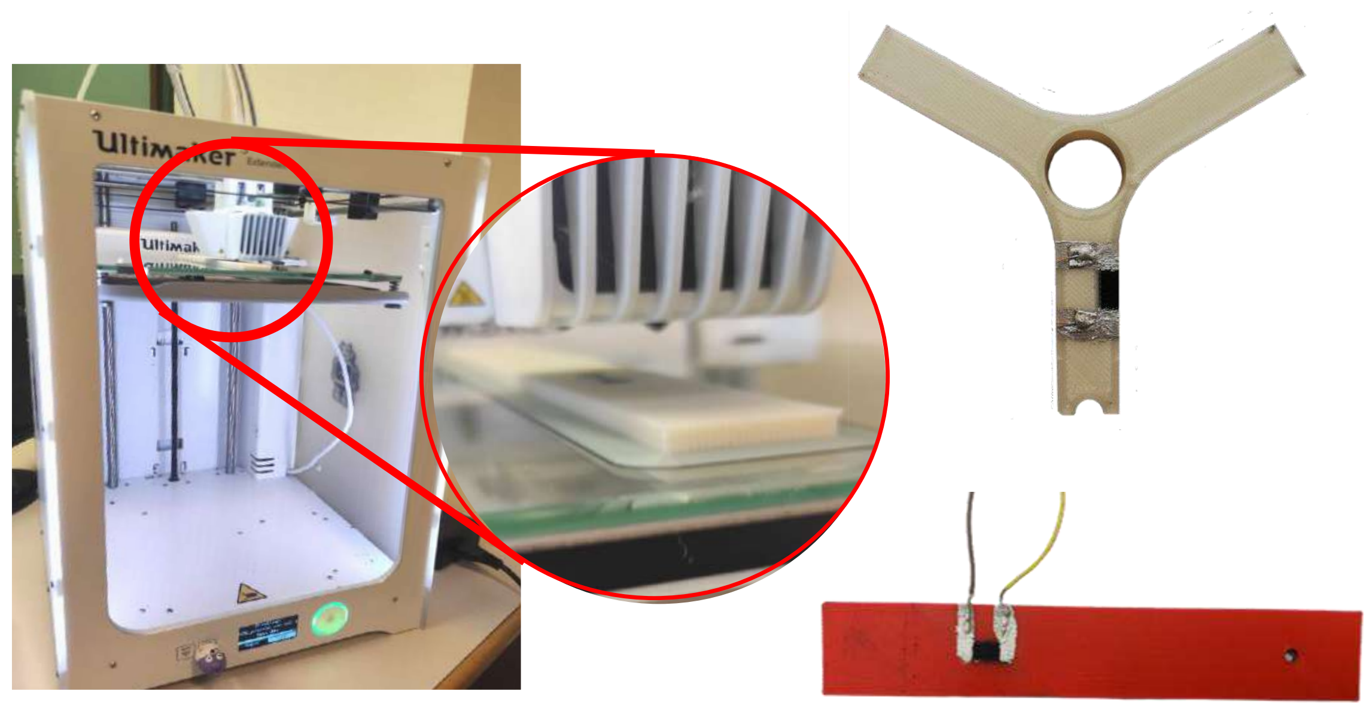

Figure 2 - Sample creation with embedded sensor and different types of samples

In our research, we use conductive materials, specifically conductive PLA, to explore the creation and optimization of 3D printed sensors and smart structures. Conductive PLA is a thermoplastic material made of polylactic acid (PLA) filaments with the addition of conductive particles such as graphite powder, carbon black, carbon fibers or carbon nanotubes, making it an electrically conductive material, more precisely a piezoresistive material, whose resistance varies with deformation. The change in resistance is directly related to the change in strain caused by the application of the load, which causes a change in voltage that can be acquired and used for monitoring, as shown in Figure 3.

The aim is to build intelligent structures that can autonomously monitor physical quantities such as deformation, vibration and deformation without external sensors, enabling real-time structural health monitoring and stress analysis.

Characterization

To create effective printed sensors, a comprehensive understanding of the material and the characteristics are essential.

The environment in which the printed sensor operates is mainly subject to dynamic loads and vibrations; For these reasons, the research was structured to determine the parameters used to evaluate the performance of the sensor:

- Linearity
- Repeatability
- Usable range

First of all, a static characterization that allows the determination of the piezoresistive coefficients, which relate the variations in the resistivity of the material to the stresses applied to the structure (Figure 3).

$$[E] = [\rho][J]$$

$$[\rho] = [\rho^0]([I_d] + [r])$$

$$\begin{bmatrix} \hat{r}_1 \\ \hat{r}_2 \\ \hat{r}_3 \\ \hat{r}_4 \\ \hat{r}_5 \\ \hat{r}_6 \end{bmatrix} = \begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{13} & \pi_{14} & \pi_{15} & \pi_{16} \\ \pi_{21} & \pi_{22} & \pi_{23} & \pi_{24} & \pi_{25} & \pi_{26} \\ \pi_{31} & \pi_{32} & \pi_{3} & \pi_{34} & \pi_{35} & \pi_{36} \\ \pi_{41} & \pi_{42} & \pi_{43} & \pi_{44} & \pi_{45} & \pi_{46} \\ \pi_{51} & \pi_{52} & \pi_{53} & \pi_{54} & \pi_{55} & \pi_{56} \\ \pi_{61} & \pi_{62} & \pi_{63} & \pi_{64} & \pi_{65} & \pi_{66} \end{bmatrix} \cdot \begin{bmatrix} \hat{\sigma}_1 \\ \hat{\sigma}_2 \\ \hat{\sigma}_3 \\ \hat{\sigma}_4 \\ \hat{\sigma}_5 \\ \hat{\sigma}_6 \end{bmatrix}$$

Figure 3 - Bridgman model equation to describe the change in resistivity due to stress

These coefficients are useful for developing detailed numerical models that can be used to simulate their behavior under different operating conditions and structures (Figure 4).

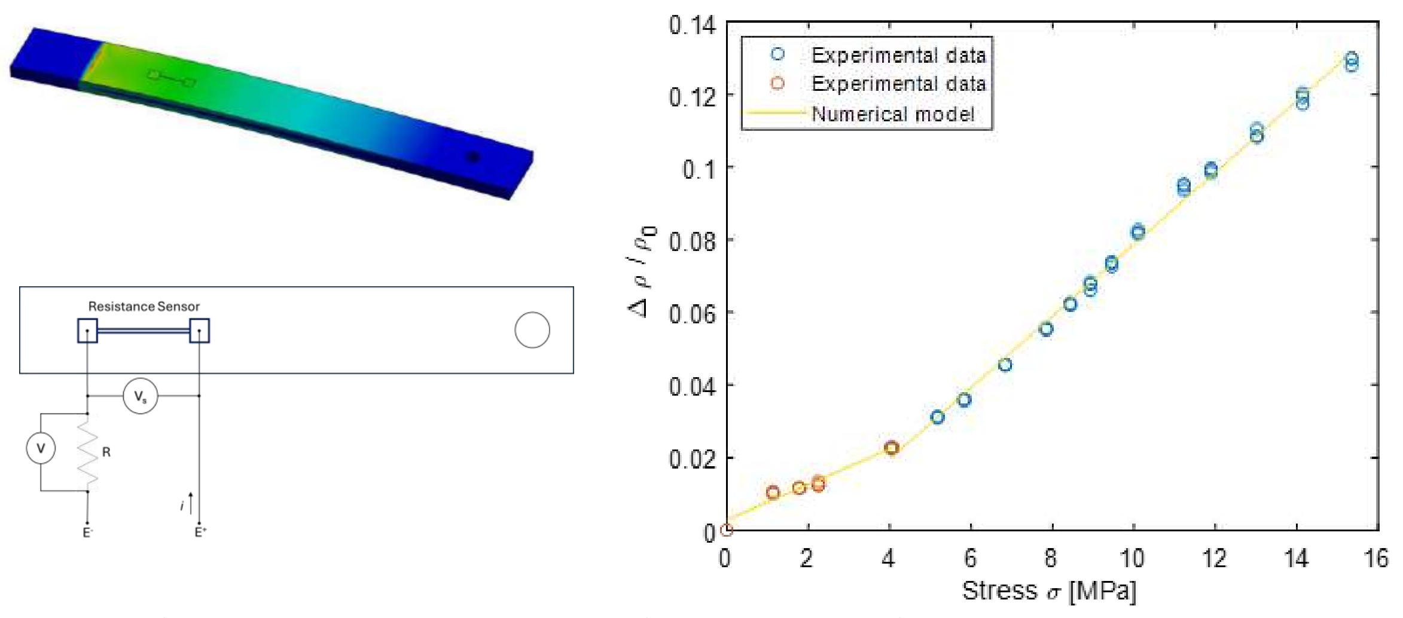

Figure 4 - FEM and schematic representation of the model and static characterization curve

Subsequently the dynamic characterization and analysis of the frequency range. This involves a series of experimental tests to evaluate the characteristics and performance of the sensor in response to time-varying input loads (Figure 5).

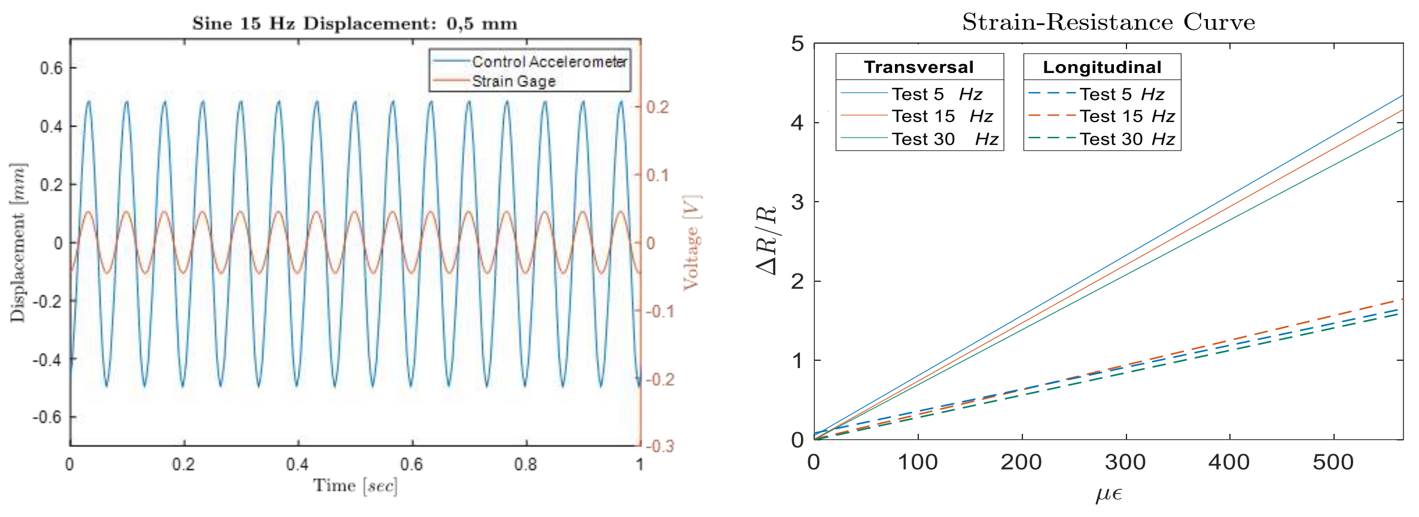

Figure 5 - Comparison between the acquired signal of the sensor and an accelometer and the dynamic resistance-strain curve

The determination of the sensitivity of the sensor with the experimental activity is used for the creation of numerical models (Figure 6) and for their validation. The comparison between which allows us to understand if the sensor is able to monitor the behavior of the structure in the frequency domain (Figure 7).

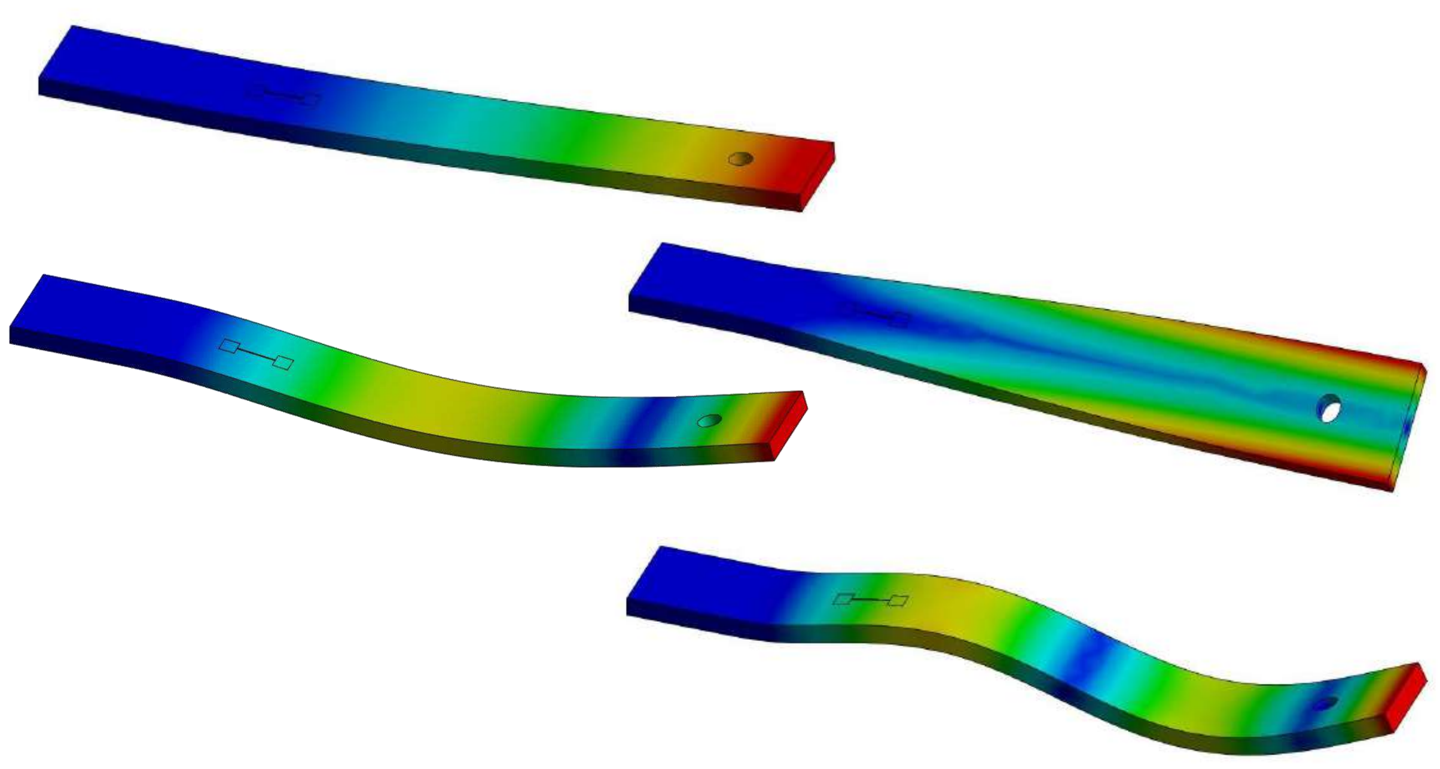

Figure 6 - Modal analysis Fem of the samples

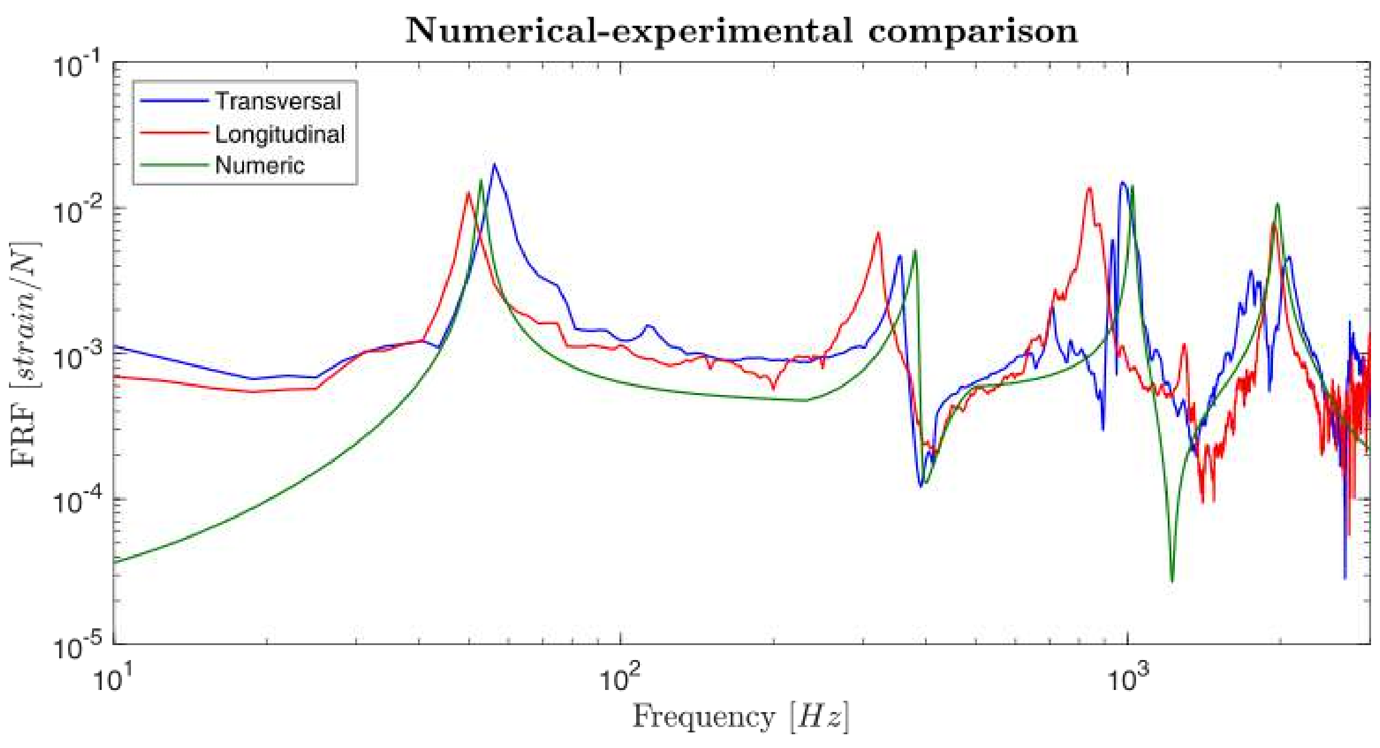

Figure 7 - Comparison of Fem model and experimental data in the frequency domain

The research also involves analyzing the sensor's ability to measure temperature, which is essential for its integration into various systems and operating conditions (Figure 8).

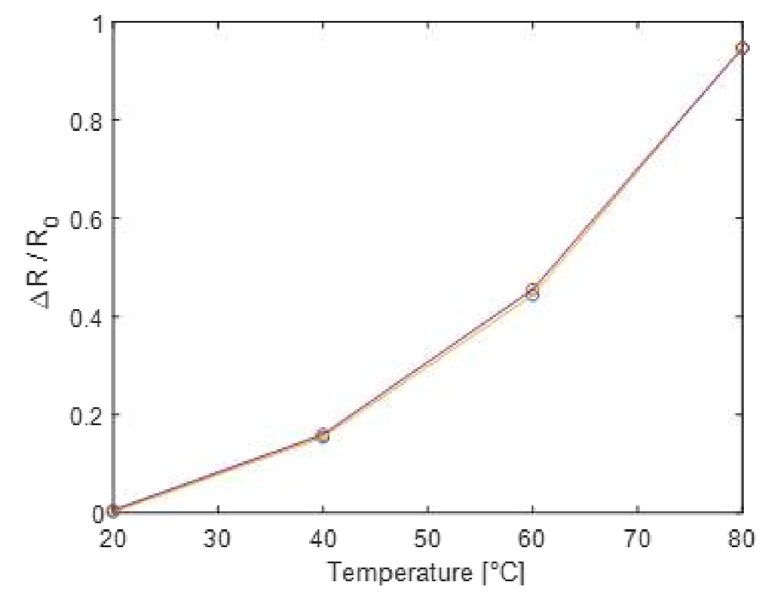

Figure 8 - Curve of resistance change as a function of temperature

Furthermore, the focus on real-time fatigue damage detection that can prevent failures and extend the life of structures (Figure 9). The sensors are designed to identify signs of fatigue damage as soon as they occur, providing timely data for maintenance and repair.

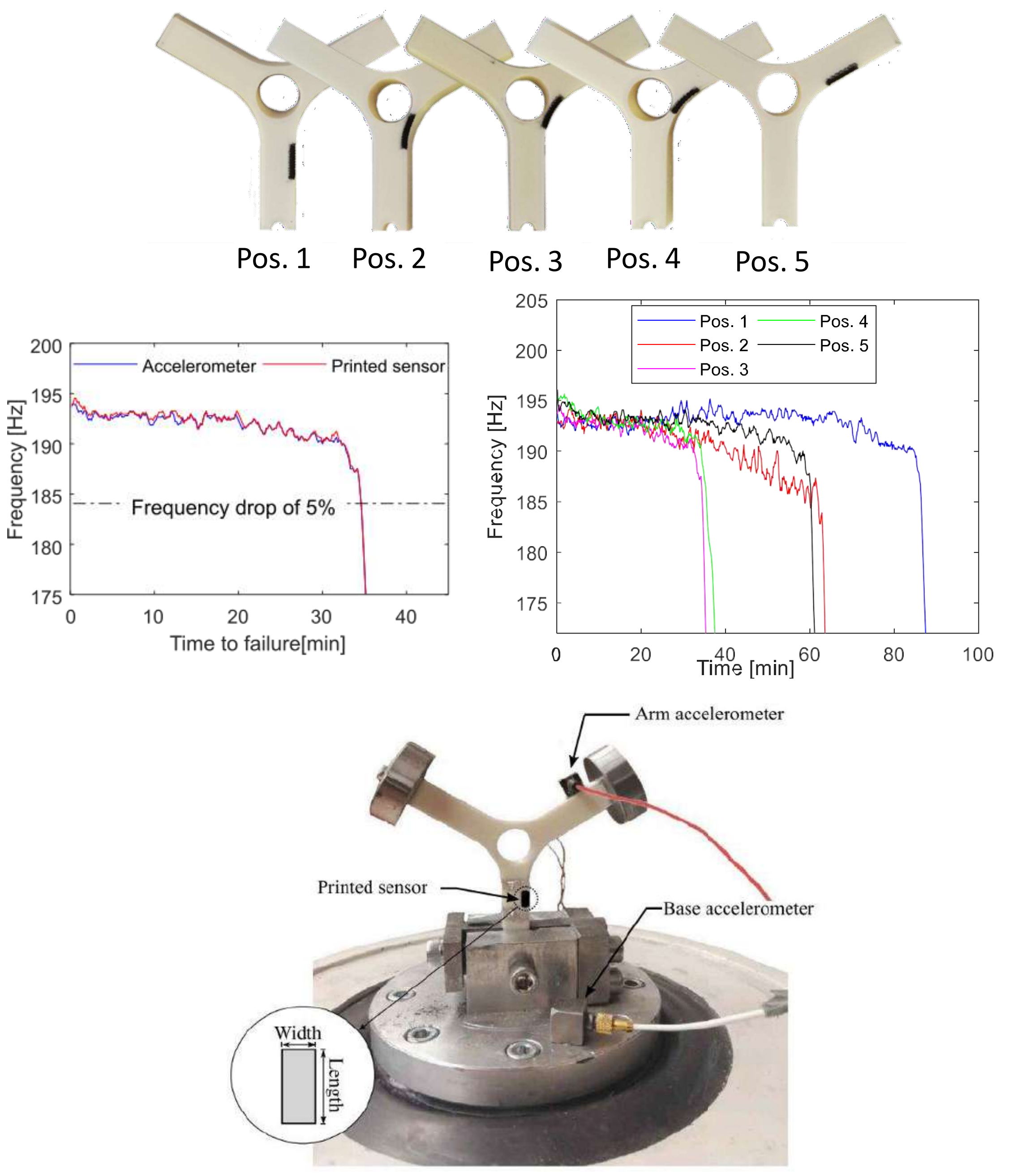

Figure 9 - Analysis of the sensor's ability to monitor the frequency drop caused by fatigue damage at different positions

Conclusion and future developments

- Implement new vibration-based damage detection techniques to monitor the condition of structures
- Development of a robust and reliable sensor capable of detecting fractures and fatigue damage in structures made with the 3D printer technique

References:

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