COMPLEX COMPOSITE STRUCTURES WITH INTEGRATED PIEZOELECTRIC TRANSDUCERS

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ABSTRACT

Nowadays, in different industrial fields as transport or aerospace, a research effort is conducted to reduce the structural weight. One of the most promising solutions is the use of composite structures due to their high stiffness, their low mass density and their low damping factor. At the same time, there is an intensification of the operational dynamic environment and an increase of durability requirements. These different expectations seem to be contradictory. One solution to manage these points is to design and manufacture smart composite structures with a fully distributed set of integrated piezoelectric transducers. These structures are able to modify their mechanical properties with respect to their environment (e.g. active vibration control), to interact with other structures (e.g. mechatronic) or with human beings (e.g. Human–Machine Interaction).

To meet the technical specifications of smart composite structures, in particular for complex geometries, it is necessary to master the manufacturing process and consequently the material parameters of the manufactured composite. Indeed, during the design phase, these parameters have to be absolutely known. A design approach based on engineering system theory and uncertainty calculation is applied to our manufacturing process of smart composite structures. In this paper, two different material identification methods (the Resonalyser technique and the Time-of-Flight technique) were selected and are applied to several test plates and, finally, on a large smart spherical cap. The Resonalyser technique is a good method to extract overall material parameters. Its major drawback in terms of cost and difficulty of implementation is the use of contactless devices for the measurements. The Time-of-Flight technique is based on the duration measurements of pulse propagation with a simple and low cost experimental setup. Integrated piezoelectric transducers are used for this purpose in the present analysis. The results obtained are quite local (mean values along the propagation path) and need a strong physical interpretation. The different material parameters obtained are compared and discussed.

Keywords: complex structure, composite structure, material characterization, transducers integration.

1 INTRODUCTION

Currently, in different industrial fields as transport or aerospace, a research effort is conducted to reduce the structural weight [1, 2]. One of the most promising solutions is the use of composite structures [3], especially the fibres-based composite structures [4], due to their high stiffness, their low mass density and their low damping factor. At the same time, there is an intensification of the operational dynamic environment and an increase of durability requirements [5]. These different expectations seem to be contradictory. One solution to manage these points is to design and manufacture smart composite structures with a fully distributed set of integrated piezoelectric transducers. These structures are able to modify their mechanical properties with respect to their environment (e.g. active vibration control), to interact with other structures (e.g. mechatronic) or with human beings (e.g. Human–Machine Interaction).

Conventionally, to functionalize a mechanical part made of composite, the piezoelectric transducers are glued on the surface of the structure and the power and control electronics are away. Our approach is significantly different. We want to develop a wide distributed network

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of piezoceramics and integrate them into the heart of the composite. The idea is to protect the transducer elements and their connections and develop some industrial products in "plug and play" mode.

To place these new features in the heart of the structures, it is necessary to integrate the transducers during the manufacturing process of composite structures. To meet this requirement, specific manufacturing methods have been developed in the laboratory IRTES-M3M of the Université de Technologie de Belfort-Montbéliard (UTBM).

Embedding the transducers is however not always sufficient to guarantee the effectiveness of the approach. A specific preliminary design strategy has then been developed. The idea is to be able to predict the final behaviour of the structure. Our approach is based on an experimental approach for determining the useful design parameters [6]. The system architecture allows to establish the needs for experimental characterization. It is necessary to have:

- *A characterization of piezoelectric ceramics.* It corresponds to the input control of piezoceramics [7].
- *A characterization of the fabricated composite.* Once the manufacturing process is stabilized, the composite must be fully characterized by a set of tests, which get access to the nominal material parameters and the uncertainty of the manufacturing process.
- *A characterization of "integrated" piezoceramics.* The idea is to develop a behaviour model, which can evaluate the drift of the electro-mechanical coupling coefficients from the input control data.
- *A characterization of the electrical interfaces.* The method of electrical connection, particularly between the transducers and the electrical grid, needs to assess the influence of process parameters on the quality of the contacts. Indeed, the electrical connection by welding technology is not used in our manufacturing process [8].
- *A characterization of the inter-element coupling.* It is necessary to evaluate the mechanical and electrical couplings between the transducers, according to the distance and connection technology, to establish dedicated design rules.

This paper is focused on the way of characterizing a manufactured composite material. Two different methods (Resonalyser Method and Time-of-flight Method) are used to extract the useful composite parameters. The paper is organised as follows. Section 2 shows the experimental setup and introduces both methods, about the theory and the way to use them. In Section 3, the design of experiments is introduced, the results as well as the comparison of the results obtained with both methods are presented. The complementary experiments on a spherical cap are introduced in Section 4. Finally, concluding remarks are given.

2 CHARACTERIZATION METHODS OF THE COMPOSITE MATERIAL

Two methods of material parameters characterization parameters (Resonalyser Method and Time-of-flight Method) are operated, for calibrated tests and manufactory process optimization.

2.1 Samples to be characterized

For characterization, five plates instrumented with four piezoceramics have been produced. The piezoceramics are positioned at each corner of the plates, as shown in Fig. 1. The characteristics of these transducers are given in [7]. In order to exploit the Resonalyser method, the dimensions should according to Poisson's plates [9] in particular to accurately determine the Poisson ratio. The manufactured material can be considered transversely isotropic. Therefore, the plates should be square. These structures are 298 mm wide and 2 mm thick with a gelcoat of 0.2 mm, as shown in Fig. 1. The plates are manufactured in the laboratory IRTES-M3M of the UTBM. This is a laminated composite composed of 6 layers of glass fibres and a polyester resin matrix. The technique of infusion is used as a manufacturing method. The fibre volume ratio is about 35%–40%. At the end, one layer of gelcoat is present on the top surface of the plate. The piezoelectric elements are placed between the first and the second layer. The layer of gelcoat is set as the reference for numbering of the layers.

2.2 Resonalyser method

Many engineering materials behave in an anisotropic manner. Their response to external solicitations depends on the loading direction. A simple but common form of anisotropy is orthotropy. The elastic behaviour of materials having orthotropic symmetry axes (e.g. rolled metal sheets or long-fibre reinforced composites), in a state of plane stress, can be described by Relation (1) between strains and stresses:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{12}}{E_1} & 0 \\ -\frac{\nu_{21}}{E_2} & \frac{1}{E_2} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} \quad (1)$$

In eqn (1), $\{\varepsilon_i\}$ represents the strain components, $\{\sigma_j\}$ represents the stress components ($N.m^{-2}$), E_i is the Young's modulus in the i-direction ($N.m^{-2}$), ν_{ij} is the Poisson ratio, and G_{12} is the shear modulus in the (1,2)-plane ($N.m^{-2}$). If the material behaviour is assumed linear, the elastic properties E_i, ν_{ij} and G_{12} are also called the 'engineering constants'. Due to the symmetry of the compliance matrix in eqn (1), only four independent engineering constants occur, e.g. E_1, E_2, ν_{12} and G_{12}.

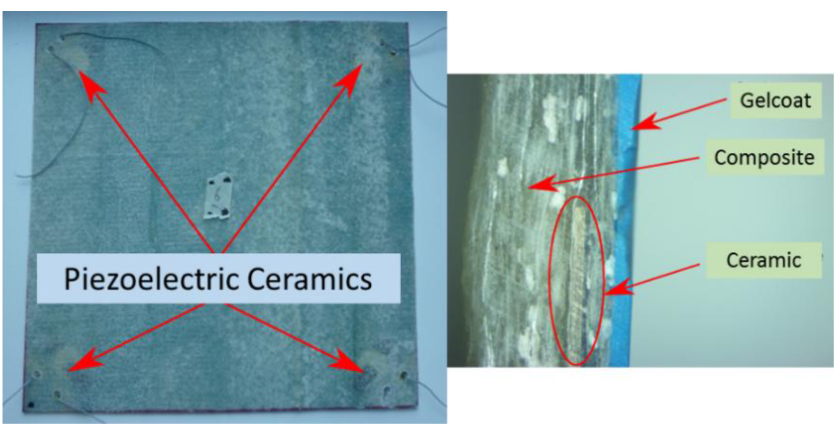

Figure 1: Samples to be tested - the Poisson's plates.

Recently, an inverse method, called “Resonalyser method”, has been developed to determine the four engineering constants for orthotropic materials [10].

The Resonalyser method is a mixed numerical-experimental method using measured resonance frequencies of freely suspended rectangular plates. Using rectangular plates as a test specimen allows the simultaneous identification of E_1, E_2, ν_{12} and G_{12}. In addition, the obtained elastic material properties are homogenised over the plate surface and hence suitable as input values for finite element models of structures. Moreover, the damages induced by the machining process of the samples is reduced with respect to the specific shaped specimens. The basic principle of the Resonalyser method is to experimentally compare measured frequencies with the numerically computed frequencies of a finite element model of the test plate. This method was introduced in detail in the PhD thesis of T. Lauwagie [11].

In Fig. 2, the experimental setup for characterization is presented. A loudspeaker is used as a contactless exciter, with a laser displacement sensor. A function generator (Keithley, 3390) is used, to create an input sine wave in the frequency range of 15 Hz – 185 Hz. The first natural frequencies of the structure are measured, with a conventional manual method based on a digital oscilloscope (Pico Technology, PS 4424).

2.3 Time-of-flight method

This material characterization method exploits the ultrasonic wave propagation properties, particularly, the Lamb waves [13]. Such waves have the particularity to spread over long distances in the composite [14]. To generate and capture the wave trains, the piezoelectric

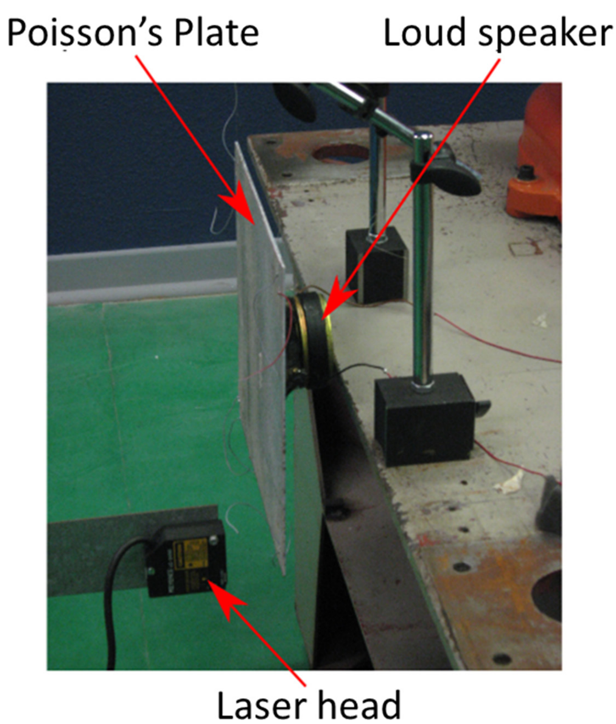

Figure 2: Experimental setup for Resonalyser method.

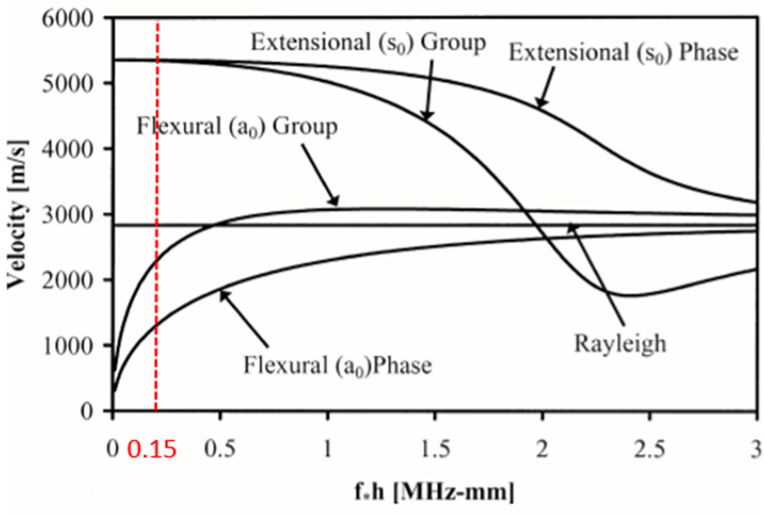

Figure 3: Dispersion curves (group velocity and phase velocity) [12].

transducers integrated into the composite are used. The transducers have a resonant frequency of the radial mode measured in the air around 100 kHz [7]. Once incorporated into the composite by *backing* effect, the central frequency of this radial mode decreases up to 80 kHz. Then the frequency-thickness product (f.h) is of 0.15 MHz.mm, shown in Figure 3. The phase velocity and the group velocity of the symmetric mode S_0 are then equivalent. So it is possible to measure the S_0 group velocity with using the formulas of extraction of the material parameters developed for the phase velocity [13].

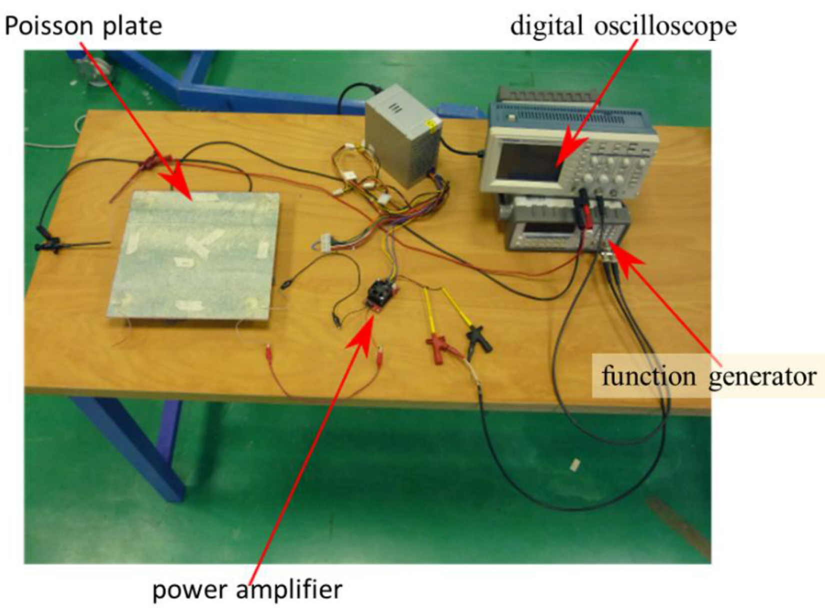

Figure 4: Experimental setup for Time-of-Flight method.

Figure 4 shows the experimental setup to measure the wave trains. A function generator (Keithley, 3390) is used to generate excitation signals via a miniature power amplifier (PiezoDrive, PDM200B). The signals are then captured via a digital oscilloscope (Pico Technology, PS 4424).

3 EXPERIMENTS AND RESULTS

3.1 Assumption of the model

At the beginning, the idea is to test the appropriateness of the methods used in relation to our need for characterization and our goal for the preliminary design of adaptive composite structures. A set of assumption is developed to simplify the model. Firstly, for the composite properties, a transversely isotropic model of the homogenised material is considered. The symmetry axis is the thickness axis. For the dimensions of the structures, the assumptions of the theory of Kirchhoff-Love plates are considered [15]. Moreover, the material is assumed in the state of plane stress ($\sigma_3 = \tau_{13} = \tau_{13} = 0$). Then, with all the assumptions, eqn (1) becomes eqn (2):

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E} & -\frac{\nu}{E} & 0 \\ -\frac{\nu}{E} & \frac{1}{E} & 0 \\ 0 & 0 & \frac{2(1+\nu)}{E} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} \quad (2)$$

The glass fibres are randomly distributed in the plane of the piles. Consequently, the value of Poisson ratio is between the Poisson ratios of the glass fibres ($\nu = 0.2$) and that of the resin ($\nu = 0.4$). So, for the Time-of-Flight method, the Poisson ratio is around 0.38. Finally, the mass density of the composite material is around 1,630 Kg.m^{-3} while the mass density of the gelcoat is around 1,100 Kg.m^{-3}.

3.2 Resonalyser method

For the numerical model, the Comsol Multiphysics software is used. Firstly, a Poisson's plate model is implemented, with a set of initial parameters (E_1, E_2, ν_{12} and G_{12}). Secondly, this model is connected to Matlab, with a specific program outputting the eigenfrequencies of the plate. Then, the experimental eigenfrequencies of the five plates are measured. Only the first five modes of vibration are considered. The nominal values of each frequency are in Table 1. At last, an optimisation loop is implemented to find the optimal material parameters by minimising the error between the experimental and numerical eigenfrequencies. The results are shown in Table 2, and the optimisation process is shown in Fig. 5. Moreover, a correlation step is necessary to identify and match the numerical and experimental eigenshapes.

3.3 Time-of-flight method

To avoid issues related to the determination of the centroid of the S_0 symmetrical lamb wave train, the excitation signal is a pulse and the duration of the flight time is determined by the

Table 1: WMean values and standard deviations of the first five eigenfrequencies for 5 Poisson's plates.

Mode	1	2	3	4	5
Frequency (Hz)	34.7	55.2	74.4	91.6	166.6
Standard deviation (%)	10.7	10.7	3.3	6.8	6.5

Table 2: Material parameters extracted with the Resonalyser method.

E_1	E_2	ν_{12}	G_{12}
12.0 e^9		0.35	3.5 e^9

rising edges of the pulse and the received signal. Only the paths along the diagonals of the plates are operated in this study to limit the boundary parasitic effects. The group velocity obtained is around 3,380 m/s. The measured phase velocity being related to the mechanical properties [13], by using eqn (3), it is possible to determine a Young's modulus E = 14.9 GPa ±15.1%.

$$c_{ph}^{s_0} = \sqrt{\frac{\rho E}{1-\nu^2}} \tag{3}$$

3.4 Comparison of the results and discussion

The Young's modulus values obtained from both methods are in quite good agreement for the considered structures. The relative difference is around 20%, which seems reasonably low considering the various excitation types and frequency domains used in the two techniques. The Time-of-Flight method will be mainly considered in our future research, since it is simple and quick to set up and external device requirements are limited. Of course, there is still some difference between both results. Among others, the difference in characterization scale explains a part of the discrepancies. The Resonalyser method is an approach based on the modal responses of the structure. The obtained values are global. The Time-of-Flight method is based on the propagation of guided waves along a particular path. Consequently, the measured values are local and more prone to variability in the material properties. Finally, it should be emphasized that, it would be interesting to perform a calibration of the shear modulus.

4 COMPLEMENTARY EXPERIMENTS ON A SPHERICAL CAP

To test the validity of the Young's modulus obtained, an experiment has been carried out to predict, in a preliminary design phase, the vibration behaviour of a spherical cap. This structure is made of the same composite material as the Poisson's plates. The results obtained are then compared with the measurements made on a prototype. The experimental setup is depicted in Fig. 6.

The numerical model of the spherical cap has been developed under Comsol Multiphysics software. The first two natural modes of vibration have been used for the comparison. The results from the numerical model and experiments are presented in Table 3.

As shown in Fig. 6, the use of draining nets during the manufacturing process creates a more flexible structure for specific natural modes, in particular for numerical Mode 2. Moreover, the thickness of the structure is far from being uniform over the entire structure and thus creates significant changes in stiffness. This probably explains the observed difference

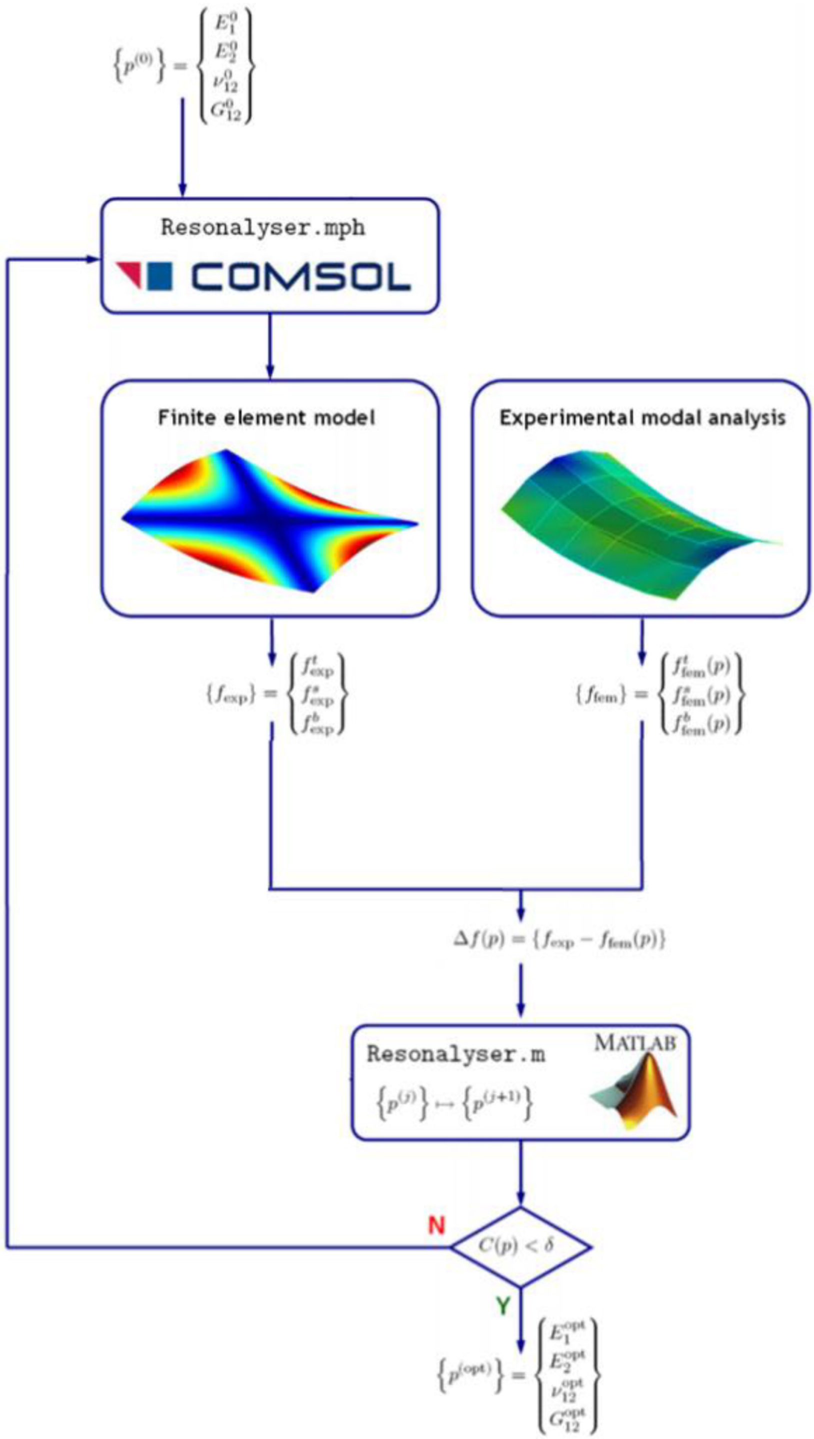

Figure 5: Modified architecture of the Resonalyser method.

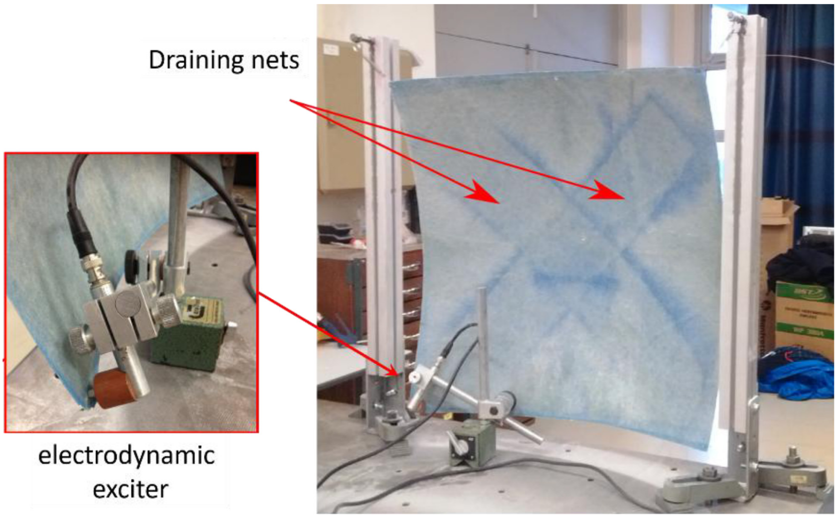

Figure 6: Experimental setup for the modal analysis of the spherical cap.

Table 3: Comparison of the experimental natural frequencies, the numerical ones from the Resonalyser method and the numerical ones from the Time-of-Flight method.

Frequency (Hz)	Experiment	Resonalyser method	Standard deviation (%)	T-o-F method	Standard deviation (%)
Mode 1	18.75	22.6	20.5	25.5	36.0
Mode 2	25.9	13.1	48.3	16.5	35.1

between the numerical and experimental eigenfrequencies. As this is the preliminary design phase, the deviation remains quite acceptable. Furthermore, according to this study, the choice of the characterization method has not a significant impact on the difference between the numerical and experimental results.

5 CONCLUSION

In this article, two non-invasive methods for identification of composite parameters have been used and compared, the Resonalyser method and the Time-of-Flight method. These data are used to find reliable parameters for the preliminary design of adaptive composite structures. Poisson's plates are fabricated and characterized via these methods. In the first approach, a set of modelling assumptions for the material behaviour is formulated to simplify the identification of a few parameters while demonstrating the difficulties and the interest of the approach. The impact of variability of parameters due to the manufacturing process is very important on the final response of the structure. But this impact is difficult to quantify during the preliminary design phase because the specific manufacturing steps are not known. A natural question arises: is it necessary to accurately know the material parameters as this design stage? The answer is negative in most cases. Indeed, a numerical model allowing to coarsely simulate the behaviour of the structures may be sufficient. Of course, the detailed design phase needs accurate material parameters and consequently accurate identification processes.

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