STRUCTURAL DYNAMIC CHARACTERIZATION OF A PLATE TYPE ELEMENT ORIENTED AT ACTIVE CONTROL IMPLEMENTATION

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Abstract: -. Successful implementation of an active vibration control system is strictly correlated to the exact knowledge of the dynamic behavior of the the system, of the excitation level and spectra and of the sensor and actuator’s specification. Only the correct management of these aspects may guarantee the correct choice of the control strategy and the relative performance. Within this paper, some preliminary activities aimed at the numerical and experimental dynamic characterization of a plate type test article as well as the evaluation of piezoelectric sensors and actuators will be presented and discussed. All these information represent, in-fact, the basic information for a successive choice and implementation of the more appropriate active control strategy.

Key-Words: - Active vibration control, structure dynamics, piezoelectric materials

1 Introduction

The evolution of automobiles, as well as many other means of transport, is a process that concerns not only with the fields of performances and aesthetic qualities, but also with comfort and environmental aspects.

Looking at the automobile sector, as an example, the necessity to develop lighter cars and the use of downsized reshaped thermic engines to reduce CO2 emissions implies the unsuitableness of the already-used soundproofing systems.

This is not a negligible problem, because high overall noise level, as well the presence in noise spectra of specific components (as those related to various rotating elements) could be perceived by buyers as a low quality indicator, in addition to represent a notable annoyance factor.

All these considerations give evidence of the importance to develop new and more efficient noise insulating materials and technologies as those generally referred as “active control technologies”.

The opportunity to use these latter technologies could help toreduce the overall weight of the acoustic treatments that can produce an increment of consumption and amore considerable environmental impact.

2 Active control strategies

Before describing the specific functions and implication of this control technique, a first definition of “Active Control” and “Passive Control” concepts may be introduced.

Passive Control may be defined as the optimization of any mechanical system (in our particular case, a structure) to limit vibrations in its standard working conditions. So, passive control systems are essential parts of the structure.

Active Control is a technological approach based on the “destructive interference” phenomenon: the sum of two signals, which are equal in amplitude but opposite in phase. Under these assumption we could say that while in the first case (passive) the control system has to dissipate energy, in the second (active) it supplies more energy to the structure for counteracting vibrations.

The necessity of integrate passive control system with active ones descends from the issue that the thickness of a soundproofing material has to be of the same order of magnitude of the wavelength of the signal to damp for being efficient: this means that, for low frequencies (typically up to 500 Hz, in some conditions up to 1000 Hz), the panel could be too thick, overloading the structure. On the other hand, active systems show application limitations due to the computational effort of the real time algorithms as well as the large amount of transducers to be implemented that generally is strongly related to the number of modes of vibration that needs to be controlled; these issues limits the bandwidth to the above mentioned 500 Hz. In addition, passive control systems have the advantage of not needing energetic supply.

Generally speaking, an active control system needs sensors, actuators and controllers, that can be combined under different control strategies: a single couple actuator-sensor with a single-channel controller or more couples with a multi-channel controller.
Three of the main categories in which we can classify the control structures are:

- Feed-Forward: ideal type for controlling deterministic-type disturbances (like engine noise). The sensors measure the disturbance signal before it arrives on the structure and send it to a pack of filters (control system), which calculates it and then generates the control signals. These are sent to the error speakers to emit the wanted control noise.

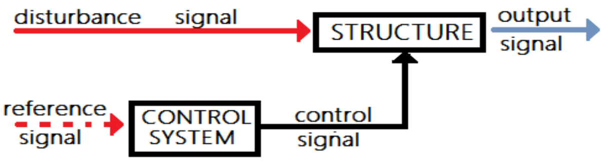


Fig. 1- Block Diagram of the Feed-Forward Control System

- Feed-Back: specific for random disturbances (aerodynamic noise, rolling tyre noise). The error signal,that has to be sent to the control system, is directly extracted from the noise emitted by the error speakers and then is sent in loop.

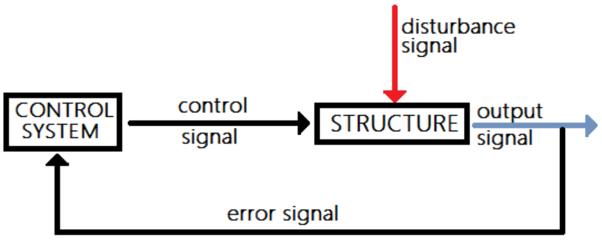


Fig 2 - Block Diagram of a Feed-Back Control System

- In some cases we can create a mixed-type control system, called Feed-Forward Closed Loop, specific for measurements of deterministic-type disturbances before they reach the structure. The control system receives one part of the signal directly from the disturbance and the other part from the error speakers.

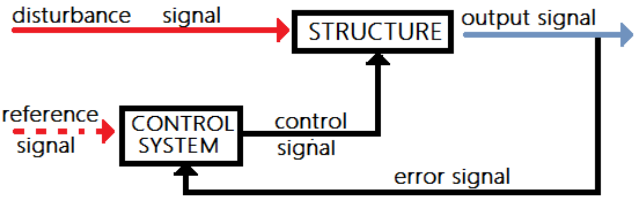


Fig 3 - Block Diagram of an adaptive Feed-Forward Control System with a feedback error evaluation

The opportunity to use one scheme or the strictly depend by the dynamic characteristic of the structure and the specific excitation field.

3 Test Article

As said in the previous sections, the final target of the proposed activity is framed in the context of improving the soundproofing in cars' cabin.

In a more detail, the final aim is to control and to reduce noise, produced by vibrations of metal panels of the body of a car. In fact, they are subjects to aerodynamic-type and rolling-type disturbances.

These perturbations depend on unpredictable factors (asphalt type, different aerodynamic conditions); sophisticated and expensive control structures, which have problems of reliability, stability and cost, are so often required.

For this reason the present activity tends to develop a structurally simple, cheap and easily replaceable active control systems. A possible approach will be the active feed-back single-channel control, composed by piezoceramic patches with integrated sensors, whose overall effect may be synthetized as an increment of the structural damping.

Before the experimentation on the real test article that represent the final target of the study (panels of the body of a real car), a first preliminary study on an simpler test article and in more controlled laboratory conditions has been decided to be experienced.

The mock-up chosen as test article for this preliminary study is a simple aluminum plate, since metal panels in cars can be considered as plate-type components.

The aluminium plate has a thickness of 1,5mm, and total dimensions of 505 x 405 mm. The plate is clamped on the edges with two iron frames, which are applied to both faces and fixed with screws, which pass through the plate too (Fig. 5 and 6).

The free surface, which isn't covered by two iron frames has dimensions of 444 x 344 mm.

In the following images the test article is showed and compared with a digital mock-up, created in a C.A.D. 3D Catia environment (Fig. 4).

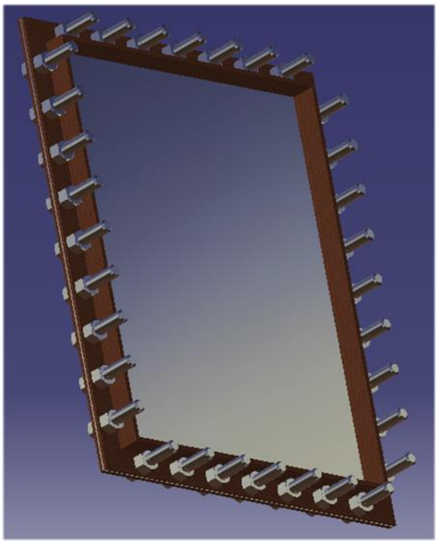


Figure 4: 3D view of the C.A.D. model.

On the plate are installed three square-shaped piezoelectric components provided by Stelco GmbH. Two piezo (PPK- 23 material) are glued on the front face and marked with letters "A" and "B" (Fig. 5).. Another patch (PPK- 11 material) is glued on the back face and marked with letter "C" (Fig. 6).

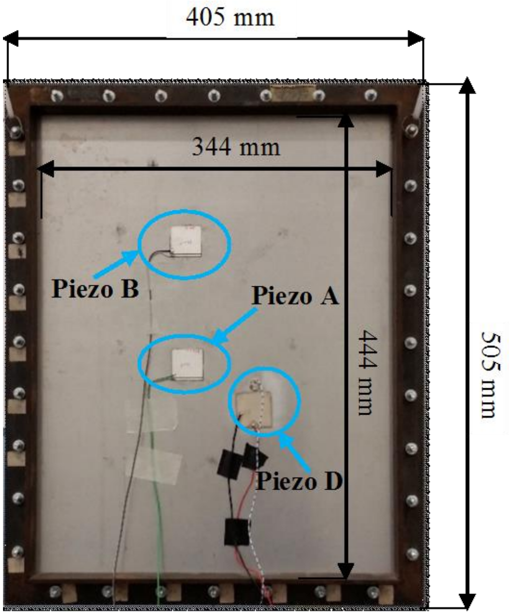


Figure 5: Front view of aluminum plate

Besides another piezo is installed on the front side of the plate, marked with letter "D", it will be used as actuator to excite mechanically the plate in the experimental tests (Fig. 5).

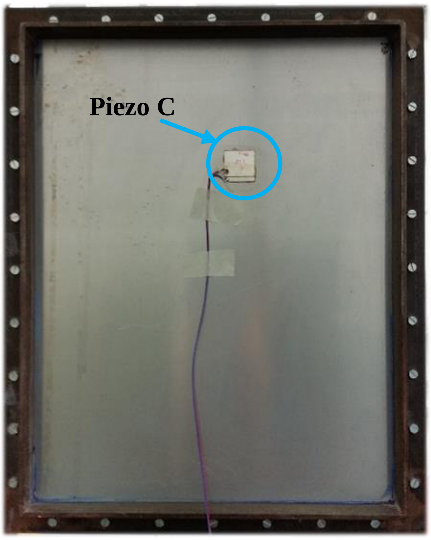


Figure 6: Back view of aluminum plate

4 Dynamic Characterization

As first step, the plate has been characterized, both under the numerical than experimental point of view.

The numerical approach used a standard Finite Element Method code whose mash has been directly derived from the CAD model. Quad type element have been used for the discretization because of the low thickness to dimension ratio of the component.

Table 1: Frequencies of numerical dynamic characterization

MODE OF VIBRATION	NUMERICAL FREQUENCY [HZ]
1^{ST}	75
2^{ND}	127
3^{RD}	171
4^{TH}	220
5^{TH}	318
6^{TH}	332
7^{TH}	418

After the numerical analysis an experimental one is performed.

A piezoelectric actuator has been attacked on the plate for working as the actuator of the perturbation signal. This was placed with a horizontal offset (measured from the left internal face of the frame to the left face of the actuator) of 190 mm and a vertical offset of 158mm (between the lower faces).

Then, the plate has been hanged up by the corners to a rigid structure (Fig. 4).

Figure 7: Plate hanged up to the frame.

The disturbance input was a Swept Sine signal with a 2000Hz bandwidth and 0.4 seconds of Sweep Time, through wich the piezo D has been stimulated (after that the signal voltage was powered up by the use of a specific piezo amplifier).

To measure vibrating levels a Polytec PSV-400 laser vibrometer has been used.

Polytec PSV-400 was placed 1,80m far from the suspended aluminum plate and it was used also as generator of the exciting signal.

The scanning grid was composed by 77 scanning points (7 x 11) and the scan was accomplished with a resolution of 1600 FFT. After the scan, was completed the SW permitted to extract the operational deflection shape at selected frequencies. Following the standard procedure for this instrument, on the basis of the SUM FRF, main peaks were selected because identified as the those corresponding to the structural normal modes and relative deformed shapes were extracted.

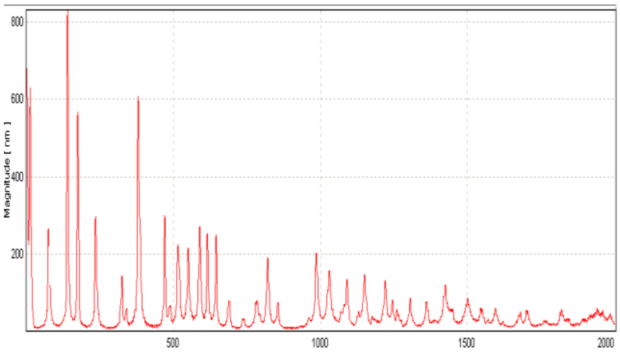


Figure 8: Diagram of displacement (nm) vs frequency (Hz)

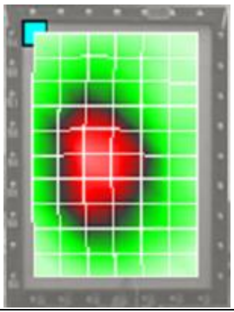
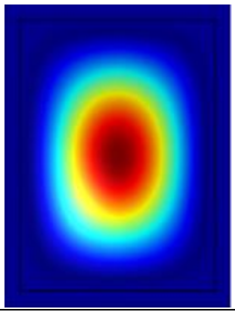
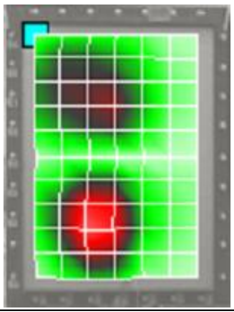
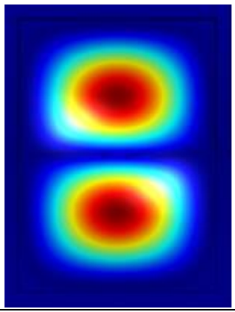
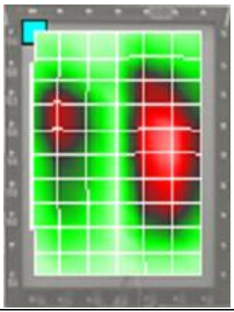
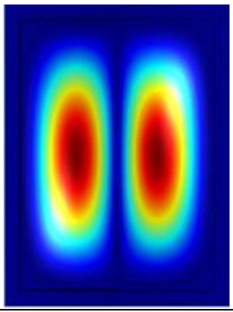
The Experimental results are summarized in Table 2, where a comparison with numerical frequencies is proposed.

Table 2: Experimental/ Numerical Modal Frequencies

Vibration Mode	Experimental Frequency [Hz]	Numerical Frequency [Hz]	$\Delta f\%$ 100* (f_{exp}-f_{num}) /f_{exp}
1ST	80	75	6.25
2ND	140	127	9.29
3RD	172	171	0.58
4TH	240	220	8.33
5TH	325	318	2.15
6TH	378	332	12.17
7TH	466	418	10.30

In the following Table 3 a comparison between numerical and experimental modal shapes is than reported.

Table 3: Experimental/ Numerical Modal Shapes

MODE	EXPERIMENTAL	NUMERICAL
1st		
2nd		
3rd		

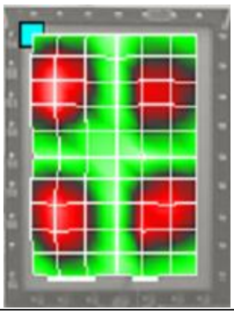
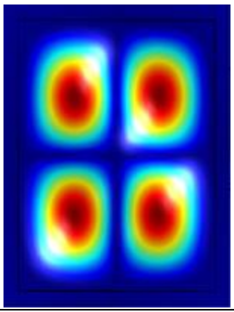
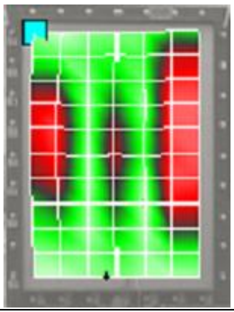
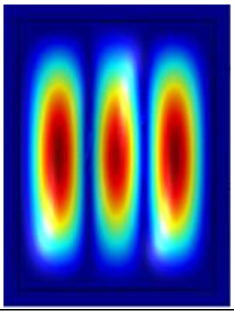
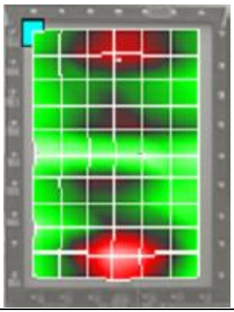
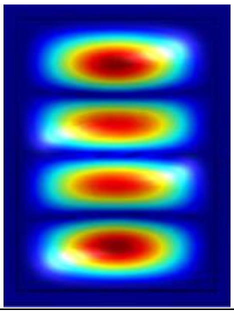
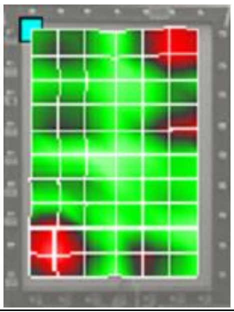
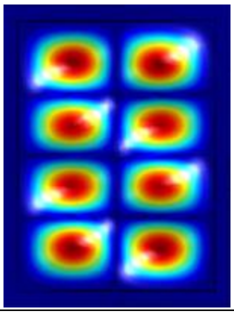
4th		
5th		
6th		
7th		

Table 2 let assume that a very good correspondence is found about numerical and experimental modal frequencies. In fact the maximum error is equal at 12% for the 6TH mode and is less than 10% for the others.

Also modal shapes show a very good correspondence between them with the same number and position of lobes for every modal shape.

This is the sign that the numerical F.E.M. model simulates in a correct way the dynamic behavior of the metal plate.

To evaluate the number of actuators and their gains required for a potential control system of a metal plate, an experimental campaign, described in the next section has that been performed

5 Evaluation of Piezoelectric Actuator/Sensor Effect

The final goal of this experimental activity was the determination of two main aspects:

- on one hand, the determination of the overall vibrational energy associated to the voltage supply of the piezo. This parameter will become fundamental once the primary vibration field (as that measured on a real car element) will be available. The main principle of an active control is, in-fact, the vibration suppression by the use of a signal whose magnitude is equal to the disturbing one and whose phase is 180° delayed. Phase control mainly depends from the controller, but overall energy level is a limitation of the actuator and its relative power supply.
- On the other hand, the voltage level that piezosensor (piezo patches that work as sensor in the control architecture) generate under the working condition. These signal, are in fact, used in th control loop as reference and error signal and relative amplitude strongly influence the gains that the control algorithm has to manage.

The experimental set-up was so composed by:

- the aluminum plate, described it the third section and hanged up by the corners to the frame;
- the four square piezoelectric, mentioned in the two previous sections;
- a PCB Piezotronics 356A16 piezoelectric accelerometer as a sensor. This is a triaxial high sensitivity accelerometer, with a ceramic shear sensing element;
- a V8 eight channel modulus on a LMS Scadas Mobile 05 as acquisition interface;

Acquisition interface converts an analog input signal (which is the electric signal emitted by piezoelectric sensors and accelerometer) in a digital one, which can be sent to the computer and elaborated by the software. The software used for the extraction of the acquisition data was LMS Testlab©, which is the one dedicated to work with LMS interfaces.

In this experimental activity a square piezoelectric, marked as "D" (Fig. 5) was used as actuator and the others are used as sensors.

In every session of measure, accelerometer takes measures in one of the nine points of a grid, arranged on the plate.

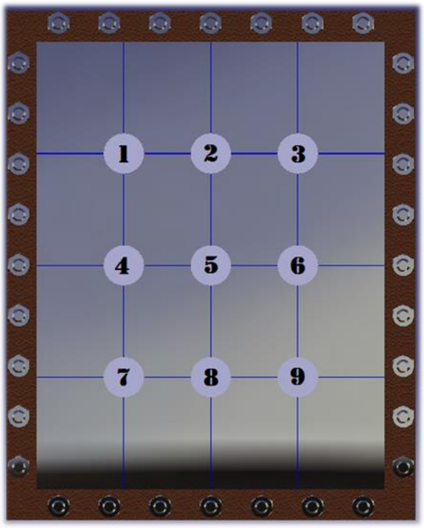


Figure 9: Grid points on the face of the plate

Each measure has been so identified with a letter joined to a number. The letter is equal to the one of the label of the piezoelectric element, which is used as actuator, instead the number is linked to the position of the accelerometer on the points of the grid.

The disturbance signal was a swept-sine wave with a 1000Hz bandwidth, 0.4 seconds of Sweep Time and 15V of amplitude.

The actuator's signal was acquired using the amplifier's monitor output, and it was used as reference for the elaboration of the FRFs. So, from each session of measure we obtained four FRFs, three from the piezoelectric sensors and one from the accelerometer, to analyze.

The data, captured by the LMS Testlab software, were exported as .MAT files, so we've been able to compute them with Matlab© to extract tables and diagrams of our interest.

After the creation of a specific Matlab scripts, the first computing step was the extraction of two tables, in which were respectively listed the values of amplitude and phase angle acquired in the 9 points at the first seven modal frequencies of the plate. In addition to condensate graphically this information, the interpolating surface of acceleration values for each of these frequencies were plotted to display the highest values of acceleration. An example of these pictures is reported in next figure 10.

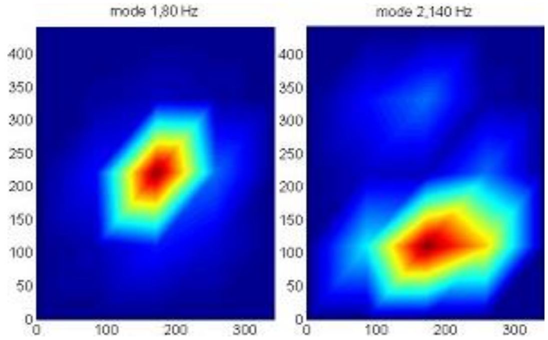
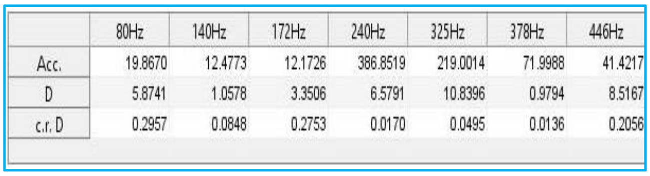


Figure 10: Interpolating Surfaces of acceleration values for the first two modal frequencies

After this, we've made a comparison of the values extracted in the measures A.2 and A.8 (actuator is piezo A and measures of acceleration with accelerometer are performed respectively in point 2 and 8 of the grid), in which the distance between the accelerometer and respectively the B and D elements are the shortest. From the A.2 measure (distance between accelerometer and piezo B's centre: 55mm) we've extracted the values acquired by accelerometer and piezo elements B and C, since they're in the same position respectively on front and back faces of the plate, so we can make a comparison between characteristics of PPK-23 and PPK-11.

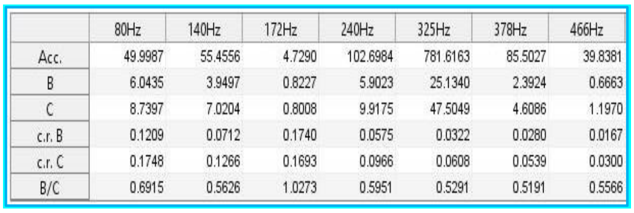
In addition we've calculated the Conversion Ratio (function of the frequency) of the B and C elements, defined as the ratio between the values of voltage recorded by the piezoelectric elements and the ones recorded by the accelerometer. In this way we can correlate a signal of tension produced by piezo with a level of acceleration. All these values are organized in Tab. 4.

Then same process has than been performed for A.8 measure (distance between accelerometer and D's centre: 32,5mm), calculating the Conversion Ratio for D piezo element.



	80Hz	140Hz	172Hz	240Hz	325Hz	378Hz	446Hz
Acc.	19.8670	12.4773	12.1726	386.8519	219.0014	71.9988	41.4217
D	5.8741	1.0578	3.3506	6.5791	10.8396	0.9794	8.5167
c.r. D	0.2957	0.0848	0.2753	0.0170	0.0495	0.0136	0.2056

Table 4: A.2 Measure: amplitudes of signal by Accelerometer [mm/s^2], by Piezo B and C [V] and calculation of c.r. Conversion Ratio [V/mm/s^2]



	80Hz	140Hz	172Hz	240Hz	325Hz	378Hz	466Hz
Acc.	49.9987	55.4556	4.7290	102.6984	781.6163	85.5027	39.8381
B	6.0435	3.9497	0.8227	5.9023	25.1340	2.3924	0.6663
C	8.7397	7.0204	0.8008	9.9175	47.5049	4.6086	1.1970
c.r. B	0.1209	0.0712	0.1740	0.0575	0.0322	0.0280	0.0167
c.r. C	0.1748	0.1266	0.1693	0.0966	0.0608	0.0539	0.0300
B/C	0.6915	0.5626	1.0273	0.5951	0.5291	0.5191	0.5566

Table 5: A.2 Measure: amplitudes of signal by Accelerometer [mm/s2], by Piezo D [V] and calculation of c.r. Conversion Ratio [V/mm/s^2]

As a generalized result, we can see that the PPK-11 model (C element) has the highest gain (conversion ratio) as sensor, so it will probably be the one that will be used in the control system.

6. Conclusions

Along this activity a numerical and experimental dynamic characterization of a metallic plate element has been assessed.

Basic information about the features of piezoelectric actuators and sensors at low frequencies have been also extracted.

The actuator data will be used for the dimensioning of the system, since a piezoelectric actuator can't sustain a voltage higher than 1000V per millimetre of thickness without breaking, so we must know how much energy an actuator can transmit to an entire plate based on the voltage.

In addition, the sensors data, especially the piezoelectric ones, are essential to understand the gains: a too low gain implies the possibility of not perceiving small displacements, and so the active control system could not work efficiently.

At this point, the system design can't start yet: the next step of the process is to understand which are real excitations on the panels of the body of a care and only after theses studies we'll have all the information necessary to the project.

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