Simultaneous active vibration control and health monitoring of structures. Experimental results

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***Abstract**: The paper reports some results of a research project having as object the development of a structural health monitoring strategy in which the monitoring process is doubled by an active vibration control process, hereby resulting a longer operation time of the structure. Hardware and controller issues of impedance-based structural health monitoring and active control, both based on piezoelectric sensors-actuators, are summarized.*

1. INTRODUCTION

The process of implementing a damage detection and characterization strategy for engineering structures is referred to as *Structural Health Monitoring* (SHM). Here damage is defined as changes to the material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity, which adversely affect the system performance. The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. For long term SHM, the output of the process is periodically updated with information regarding the ability of the structure to perform its intended function in spite of the inevitable aging and degradation resulting from operational environments [1], [2].

Broadly speaking, structural vibration control methods can be classified as *passive*, *semiactive* and *active control methods* [3]. The passive control is issued from the structural motion itself, and is based on certain prior structure design optimization. This kind of classical pseudo-control uses possible damper type devices; thus, no external force or energy is applied to perform the control. On the contrary, the active control is accomplished by so called active actuators, which consume external energy and deliver in system several/a number of external forces, rigorously determined by virtue of a control law, based on the measurement of the system response, materialized as unwanted, harmful vibrations, to external disturbances. Sensors are employed for measurement purposes and with the help of computers, the digital signal, converted to analogue signal, activates the active actuator. In recent years, a new class of control systems, for which the external energy requirements are orders of magnitude smaller than a typical active control system, has been evolved. They are known as semi-active control systems, in which the control action is produced by the movement of the structure itself, but is regulated by a damper type, so called semiactive actuator, consuming very small external energy.

The two invoked directions – structural health monitoring and structural active control – are usually distinct and independent tasks in technical applications. Another approach was considered in [4] and starts from the development of a synergic viewpoint: a simultaneous implementation and operation of these two methodologies, relating two research fields as applied to aerospace structures. The derived problems are complex: a) vibration definition as major factor for health depreciation; b) mathematical modeling for complex vibration systems, like aerospace structures; c) definition of a procedure for the performing depreciations at a great rate (Weibull distribution for the damage tests and fault cases, for example); d) the analysis of the usual health monitoring methodologies (modal noise, residuals, mechanical impedance, Lamb waves, neural networks, time-frequency analysis, Hilbert transform etc.) [5] and the development of a suitable monitoring methodology; e) the development of a robust active control methodology [6], [7]; f) validation of the integrated strategy methodology – health monitoring with active vibration control – by numerical and laboratory tests.

The present paper reports some results of a research project [4] having as object the development of a structural health monitoring strategy in which the monitoring process is doubled by an active vibration control process, hereby resulting a longer operation time of the structure. Hardware and software issues of impedance-based structural health monitoring and active control, both based on piezoelectric sensors-actuators, are summarized. It is worthy of note that the SHM with vibration and fatigue control including flutter suppression, alongside other active load control technologies such as gust load alleviation, manoeuvres load alleviation and optimization of adaptive wing structures, compose an inventory of technologies attentively evaluated at level 1 of the ambitious EU project SFWA [8], having INCAS Cluster as Associate Partner. Thus, the activity in the framework of the national project SIMOCA [4] was very useful from the viewpoint of the knowledge transfer in activities of the SFWA project.

The work has the following structure. Section 3 describes the implementation of an Intelligent Strategy of Monitoring and Active Control (SIMCA). Section 4 presents laboratory tests for the SIMCA validation. Section 5 summarizes some conclusions.

3. SIMULTANEOUS ACTIVE CONTROL AND MONITORING OF STRUCTURES USING PIEZO SENSORS-ACTUATORS

An Intelligent Strategy of Monitoring and Active Control (SIMCA) was implemented and tested on an elementary structural specimen – a cantilever duraluminium plate (see details in [1]). The used monitoring technique was impedance based one, associated to a monitoring Macro Fiber Composite (MFC) sensor glued onto the plate. Control synthesis was chosen as LQG synthesis [3], [4], using a MFC as actuator.

The basic concept of the impedance-based monitoring method is to use high frequency structural excitations to monitor the local area of a structure for changes in structural impedance that would indicate imminent damage. This is possible using piezoelectric sensor/actuators whose electrical impedance is directly related to the structure mechanical impedance. The impedance measurements can easily give information on changing parameters, such as resonant frequencies, that will allow for the detection and quantification of damage [9]. Thus, consider that the monitoring MFC is driven by a sinusoidal voltage sweep. Since the MFC is bonded to the structure, the structure is deformed along with it and produces a local dynamic response to the vibration. The response of the system is transferred back from the MFC as an electrical response, which is then analyzed, to attest if changes hold in the local area, as changes of the mechanical impedance of the structures, thus indicating some structure damages. The solution to the wave equation gives the following equation for electrical admittance [9].

Fig. 1 – Photo of the assembly duraluminum cantilever plate
with MFC and lute bandage for simulation of modal type damages

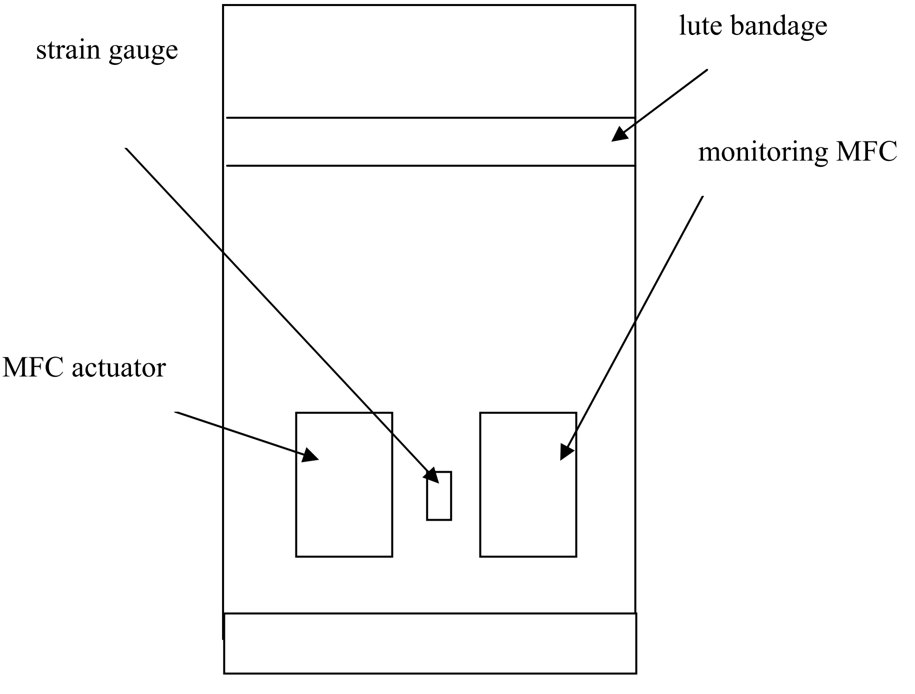

Fig. 2 – MFC actuator and sensor

$$Y(\omega) = \frac{I}{V} = i\omega a\left(\varepsilon_{33}^{T}(1 - i\delta) - \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} d_{3x}^{2} Y_{xx}^{E}\right) \tag{1}$$

where Y is the electrical admittance (inverse of impedance), I is the output current at the MFC element as sensor, V is the input voltage at the same MFC element as actuator, Z_a and Z_s are the MFC material's and the structure's mechanical impedances, respectively, Y_{xx}^{E} is the complex Young's modulus of the MFC with zero electric field, d_{3x} is the piezoelectric coupling constant in the arbitrary x direction at zero stress, ε_{33}^{T} is the dielectric constant at zero stress, δ is the dielectric loss tangent of the MFC, and a is a geometric constant of the MFC. The equation indicates that the electrical impedance of the MFC bonded onto the structure is directly related to the mechanical impedance of a host structure.

The impedance method has many advantages compared to global vibration-based and other damage detection methods; the main advantage consists in power requirements in the range of microwatts (low excitation forces, less than 1 V, combined with high frequencies, typically greater than 30 kHz).

Determining the impedance by virtue of the equation (1), or by direct measurements, is complicated and very expensive: impedance analyzers such as the HP 4194A, costs approximately 40 000 \$. To address this issue, a low cost method based on FFT analysis and an approximate evaluation of the impedance was used [9]. The electrical impedance of the bonded MFC (or piezoceramic PZT) is equal to the voltage applied to the MFC divided by the current through the MFC. An approximation of the impedance is generated by taking the ratio with the FFT analyzer of the voltage supplied to the circuit, V_i, to the voltage, V_0, across a sensing resistor, R_s, in series with the MFC, as seen in Fig. 3.

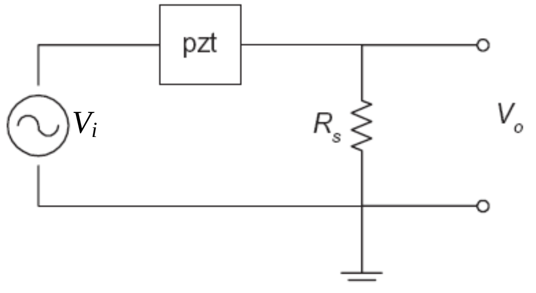

Fig. 3 – Circuit for impedance approximating

The electric circuit of the health monitoring system for the mechanical structure is shown in Fig. 4. The MFC actuator is represented in the diagram by a capacitor with a measured capacity C = 22 nF. The current I is calculated according to the relation

$$I = \frac{U_r}{R} \tag{2}$$

where the resistance R = 56 Ohms was considered as suitable. The voltage U_c on the capacitor is given by

$$U_c = U_0 - U_r \tag{3}$$

where U_0 is the voltage supply of the circuit. The impedance Z_c of the capacitor (average value) is given by

$$Z_c = \frac{U_c}{I} \tag{4}$$

where U_c , U_0 , U_r and I are the average values of the electric signals u_c , u_0 , u_r and i.

It is necessary to underline that the real part of the admittance (1) (and of the impedance too, as its reciprocal value) has a dominant role in monitoring process, as being more reactive to damage or changes in the structure's integrity than the imaginary part. On the other hand, the imaginary part is very sensitive to temperature, therefore the real part of the impedance is usually considered in the monitoring applications [10] (but not exclusively, as shown in the literature).

Starting from relation (1), or even from more simplified relations (e.g., the impedance value of a resistive-capacitive voltage divider), it is possible to make some anticipative evaluations of the operating frequency in the field of structural monitoring. Usually, the frequency range of monitoring technique for measuring the impedance is located at 30 kHz to 250 kHz. For a given structure, the specific field is found through *trial and error* method.

Peaks appearing on the measured impedance curves reflect both structural resonances and electrical resonances of piezo material. The latter ones are significantly higher than the first ones, and basically they must be eliminated during the selection frequency fields as they aren't susceptible to erosion or structural defects

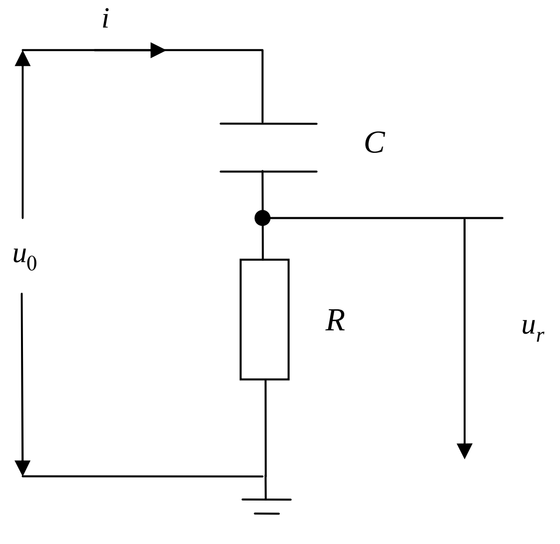

Fig. 4 – Electric circuit for low cost monitoring

SIMCA monitoring and active control strategy was implemented as it can be seen from the block-diagrams in Fig. 5 and Fig. 6. Fig. 5 shows a block-scheme for monitoring measurements. SIMCA general block-diagram of health monitoring and active control is shown in Fig. 6. The "chirp" type [11] monitoring signal and disturbance signal are generated by a functions generator (Velleman or LabView), as input signals to the MFCs. The control signal is synthesized based on information provided by a strain gauge and processed by the control PC, Fig. 6, and it is applied, with the disturbance signal, to the MFC actuator, Fig. 2.

Resistance *R* is inserted in order to obtain a low cost monitoring. Voltage and current signals are measured and processed of line and FFT is applied to calculate the impedance in different operating modes (with and without lute bandage, without and with control), thus obtaining the health monitoring signatures. Alternatively, the damage was simulated by weakening mounting screws of the plate.

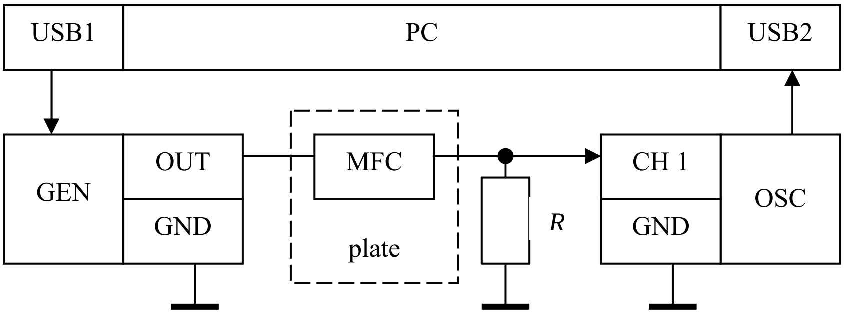

Fig. 5 – Block-diagram of the experimental setup for measuring the impedance of the cantilevered plate specimen. Legend: **PC:** computer with two USB ports and the Velleman software, PC-Lab 2000 SE; **GEN:** function generator PC-Function Generator, PCGU 1000; **OSC:** oscilloscope PC-Scope, PCSU 1000, Velleman Instruments; **MFC:** Micro Fibre Composite, M-8557-P1, Smart Material GmbH (second MFC actuator, Fig. 2); **R :** 56 Ω resistor; **GND:** ground; **Plate:** experimental specimen used by INCAS, see photo in Fig. 1

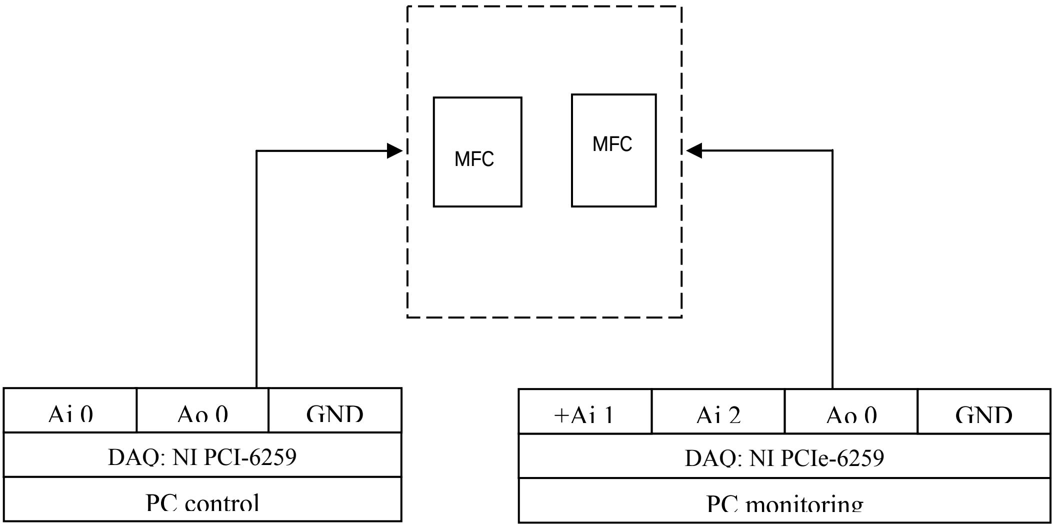

Fig. 6 – Block-diagram of the montage for SIMCA testing and validation on the specimen cantilevered plate. DAQ: multi-functional board PXI-6259, National Instruments

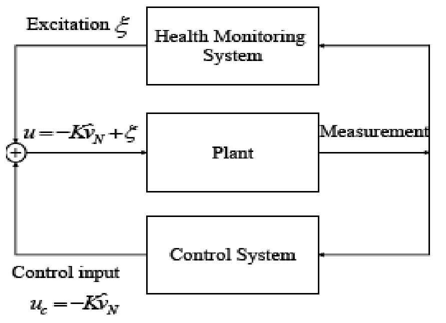

Fig. 7 – SIMCA philosophy: simultaneous monitoring and active control (monitoring signal ξ)

Fig. 8 – Hardware components of the test rig for SIMCA tests

Fig. 7 illustrates the SIMCA's outlook and Fig. 8 presents some hardware components of the test rig.

4. LABORATORY TESTS FOR SIMCA VALIDATION

Fig. 9 shows a time history of the unitary strain caused by a sinusoidal disturbance $\xi = 250 \times \sin(2\pi \times 5.1 \times t)$ [Volts] and measured by the strain gauge sensor, successively in the absence and in the presence of the control variable; the efficiency of the active control is thus proven, meaning an attenuation of vibrations of about 10dB.

When using the Velleman functions generator, the voltage u_0 (with a variable frequency and constant amplitude) is generated, for two frequency ranges, and the voltage u_r (see Fig. 4) is measured with the Velleman oscilloscope. The impedance of MFC is calculated, in accordance with the relations (2)-(4), in two variants: damaged structures and undamaged structure. A similar scenario was applied by using the DAQ NI board as functions generator, but Velleman variant was finally preferred as having a higher electric power. In this way, the same results were obtained in the same conditions.

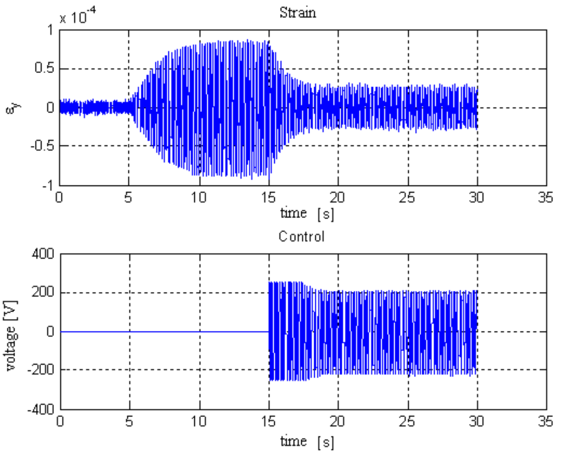

Fig. 9 – Efficiency test of the LQG control

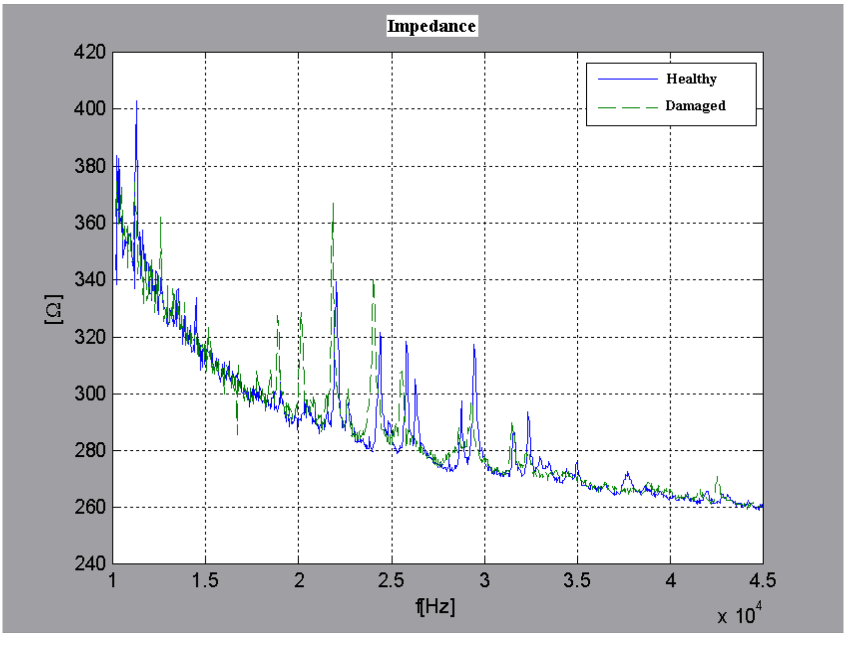

Fig. 10 – Impedance signature. Control off case, „healthy" system and „damaged" system (one of the two mounting screws was weakened)

The procedure of the MFC impedance calculation is now briefly detailed. The voltage u_r is gathered as $2{,}5\times10^5$ samples with $500\,\text{kHz}$ sampling rate (thus, the duration of acquisition is 5 seconds). The samples vector of the voltage u_r is then divided by *R*, thus obtaining the samples vector of the current *I*. FFT is applied to the vectors u_0-u_r and *I*. Finally, the impedance is found as the ratio of the two Fourier Transforms, $\frac{(U_0(f)-U_r(f))}{(I(f))}$ (*f* is the frequency). The significant impedance signatures, which legitimate the SIMCA validity, are shown in Figs. 10-12. On the one hand, the presence of „damages" is seen as an impedance peaks increasing, thus a metric of damages can be introduced. On the other hand, the control (its presence or absence) doesn't significantly influence the impedance signature, the only important effect being that of increasing the operation time of the structure.

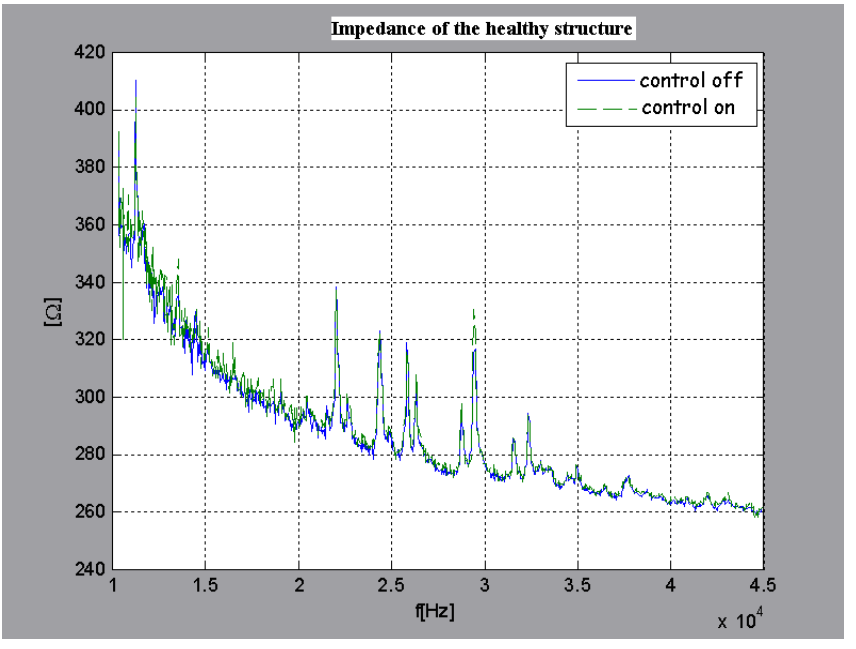

Fig. 11 – Impedance signature. Control on-off case, "healthy" structure

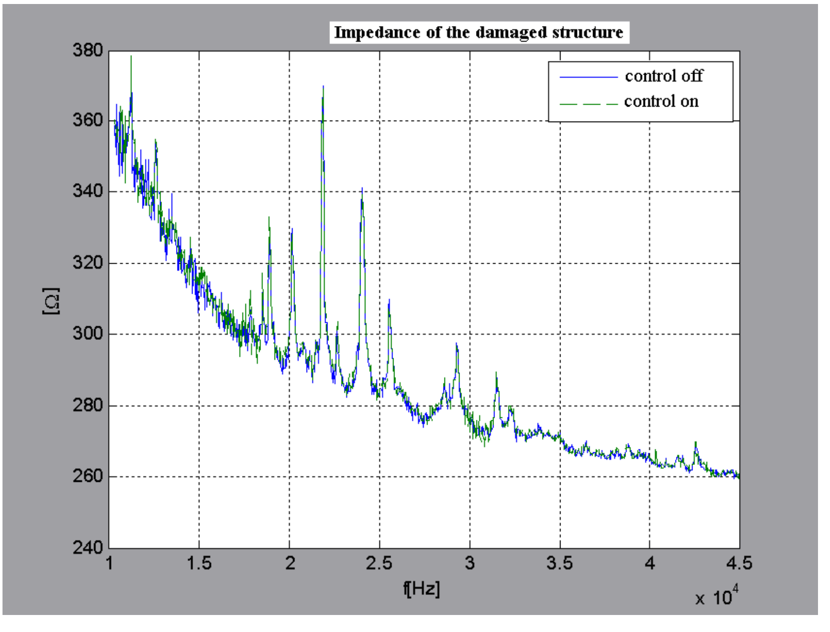

Fig. 12 − Impedance signature. Control on-off case, "damaged" structure

5. CONCLUSIONS

A strategy of simultaneous monitoring and active control of structures is experimentally validated. The signature of structure's health is represented by the real part of electromechanical impedance curves of MFC piezo sensor, attached or bonded on structure. Active control law is based on the optimal linear-quadratic LQG synthesis. Just a MFC actuator and a monitoring MFC sensor are sufficient to implement the strategy.

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