Smart carbon-epoxy laminate with high dissipation properties for vibro-acoustic optimization in the turboprop aircraft

M. Viscardi, M. Arena, G. Barra and L. Guadagno

***Abstract*—** The transport industry especially that aviation one is investing in research for innovative technologies to improve the internal comfort both in the design phase and in aircraft already operative. The vibration and noise attenuation is of course among the most relevant target in the aeronautical scientific community actually many research programs which see the cooperation between academic institutions and leading industries are promoting the development and the application of innovative materials: smart composites, SMA, piezoceramics are only few examples of this increasingly emerging field. In this paper, the latest results achieved on the self-healing laminates for their too very appreciable damping performance are presented. The effectiveness of the proposed biomimetic technology has already been assessed in terms of damping capability compared to a standard CFRC specimen. The tests evidence has revealed a really better behavior of the self-healing sample compared to the conventional one in terms of vibrational energy: the average damping coefficient, measured in two different ways has been found to be about four times higher. Therefore, relying upon the results achieved on simple specimens, a numerical model representative of an aircraft fuselage section has been developed in order to predict the levels of noise and vibrations generated by a typical propeller excitation load. A careful investigation of air-structure interaction for internal noise forecast and surface radiated power has been carried out combining the numerical solutions performed within MSC Nastran® and Actran® environments. The Finite Element approach has allowed for emphasizing that the adoption of these smart treatments could led to an average noise reduction of about 3 dB compared to the conventional laminate configuration as well as a surface vibration decrease up to 50%.

***Keywords*—** Biomimetic treatment, Finite Element, noise and vibrations, self-healing, radiated power.

I. INTRODUCTION

THE use of composite materials involves *de facto* the exploitation of many advantages such as lightness, strength, rigidity, good behavior to fatigue, ability to design the material according to its own need, but also cost reduction of manufacturing, weight and joints. Furthermore, the different parameters that determine the final behavior of a structural composite offer the designer a large field of action, in which the optimum design of the material is stated as a new discipline of structural mechanics. However, the laminates exert damping levels generally lower than metallic structures: the connecting elements such as rivets and bolts for internal friction are just localized points of vibrational energy dissipation. In such framework, the authors have experimentally assessed the considerable improvement of damping characteristics of CFRF laminates when treated with self-healing resin infused into carbon fibers. Aerospace and aeronautic structural systems experience a broad spectrum of environmental and operational loads. Severe and/or prolonged load exposures may trigger the damage accumulation process even in recently deployed structures. The process of implementing a strategy of auto-repair of a damage is a subject of increasing interest. One of the challenges for many of the already developed self-repairing systems is to enhance the structural stability and mechanical properties of the materials [2]. Such biomimetic treatment then allows on one hand to improve the reliability and the lifetime of the structural element and on the other to ensure really an appreciable damping capacity [3]. The following survey is the result of intensive cooperation between the Industrial Engineering Departments of Università degli Studi di Napoli “Federico II” and Università degli Studi di Salerno on the ambitious application of self-healing materials in primary aircraft structures, Fig. 1. Some targeted investigations already conducted previously by the same partners have highlighted the excellent damping capacity of these samples compared to standard specimens [4]. Therefore, on the basis of the results achieved in the laboratory on simple specimens, a numerical model of an aircraft fuselage section has been developed in order to assess the levels of noise and vibration generated by a typical propeller excitation load. The FE (Finite Element) modelling has allowed for emphasizing that the adoption of these smart treatments could led to an average noise reduction of about 3 dB compared to the conventional laminate configuration. Further analysis within Actran® environment have been performed to estimate the surface radiated power reduction.

Fig.1 Self-healing (SH1) panel

II. Experimental Background

The experimental tests were carried out on different compositions (Fig. 2) with the intent to select the most appropriate composition of self-healing system for aeronautic vehicles. In the paper [2], the results related to the healing efficiency and dynamic mechanical properties of self-healing epoxy formulations cured by a twostage curing cycle consisting of a first isotherm at 125 °C (2 h) followed by a second isotherm (2 h) where the temperature was set at 170 °C or 180 °C, are discussed. The used catalystwas the Hoveyda–Grubbs' firstgeneration catalyst (HG1).

Fig. 2 Different compositions of self-healing systems [2]

The results highlight that the chemical nature of the epoxy matrix of developed self-healing systems plays an important role in determining the mechanical properties of the resulting material. The use of a reactive diluent to replace the flexibilizer Heloxy 71, already used in other self-healing formulations, makes it possible to obtain better dynamic mechanical properties than the already published results for self-healing epoxy resins. The innovative biomimetic treatment for the realization of the self-repair laminates allows for, on the one hand increasing the reliability and the long-term resistance of the component, while the other provides a better vibrational energy damping capacity. The latter is often an objective sought in the orthotropic structures because even if have many advantages compared to metal ones, such as the preservation of the weight, the resistance to fatigue and corrosion, are not able to dissipate the vibration energy in the same way. An assessment of such property of two carbon fiber/epoxy coupons has been carried out by experimental tests conducted in the laboratory of Department of Industrial Engineering (Aerospace Section, Università degli Studi di Napoli "Federico II"), Fig. 3, 4 [1], [4].

Fig. 3 Composite specimens analyzed

(a) (b)

Fig. 4 Dynamic test: Standard (a), SH1 (b)

The following values represent the estimated damping coefficient using two different methods, one in the time domain and the other based on the analysis of FRF (Frequency Response Function), Table I.

Table I Damping coefficients measurement

	Time Domain	Spectral Domain
Standard	1.178%	1.73%
SH1	3.967%	5.00%

The experimental outcomes has revealed an actually better behavior of the self-healing sample compared to the conventional one: the average-damping coefficient has been found to be about four times higher.

III. Turboprop Aircraft Application

A. *Finite Element Model*

The next industrial segment where applications of self-healing materials are foreseen is the aviation industry. Use of composites in aircrafts has grown significantly in the past years. Hollow fibers reinforced composites are a possible solution to recover cracking or damages. Self-healing polymers have paved its way in space applications [3]. As part of this research project, it was decided instead to characterize preliminarily the role of these treatments within the vibro-acoustic insulation, taking a sample of a turbo-propeller primary structure like the fuselage. A typical barrel has been modelled within MSC Nastran® environment, Fig. 5: a 2D mesh (CQUAD) with cross-ply orthotropic properties simulates the 24 plies external coating (SIGMATEX (UK) LDT 193GSM (*grams square meter*)/PW (*plain wave*)/HTA40 E13 3K (*3000 fibers each tow*)) having a thickness of 2 mm except for areas interested by the plexiglass windows, with thickness of 3 mm, Fig. 6. Moreover, the structure has been reinforced by Z-stiffeners in aluminium (CBAR) [5]. The main characteristics of the numerical model are summarized in Table II.

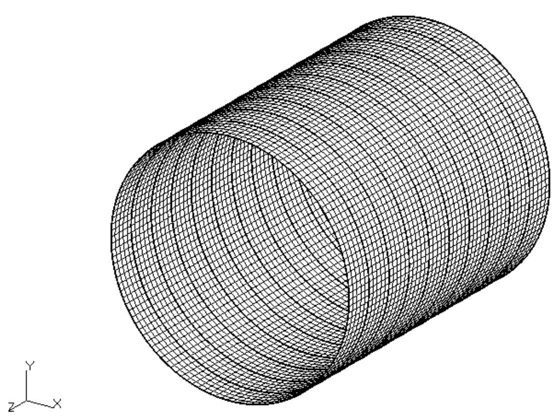

Fig. 5 Fuselage FE Model

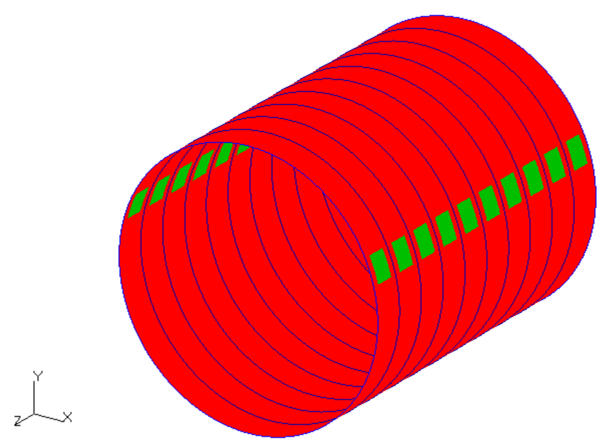

Fig. 6 FEM properties

Table II FEM Entities

Entity	**Number**
Nodes	17073
CQUAD	6300
CHEXA	9600
CBAR	1386

The aircraft section subject of the current study is positioned around the propeller plane, therefore most exposed to the noise source. The following diagram, Fig. 7, represents the characteristic tonal load exerted by the propeller. A distributed pressure was realized, such as to simulate the typical anti-symmetrical pattern along each bay in correspondence of the three blade pass frequencies (BPF), Fig. 8. All numerical analyses have been performed assuming the extreme edges constrained in the rotation around the fuselage Z-axis. A 3D mesh (CHEXA) was then coupled to the structural domain to take account of the presence of the fluid for the evaluation of the sound pressure level, Fig. 9 [5].

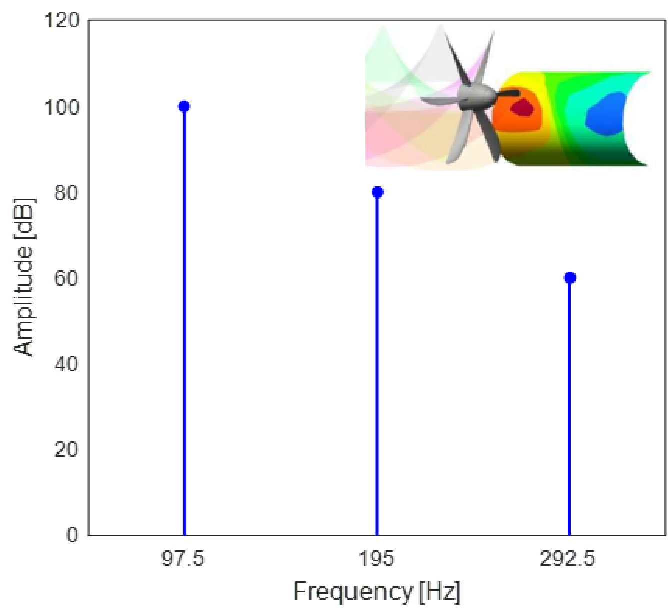

Fig. 7 Propeller tonal load, BPF

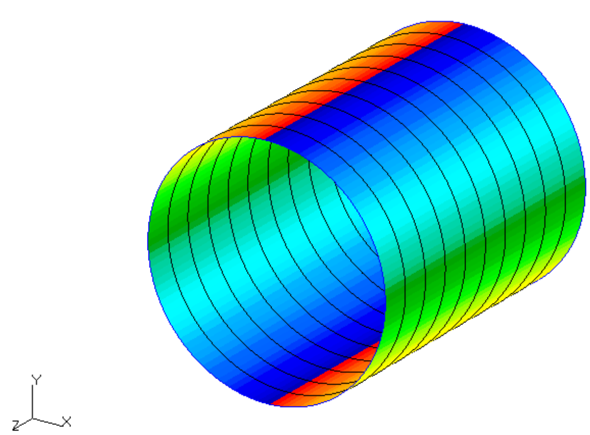

Fig. 8 External tonal load field

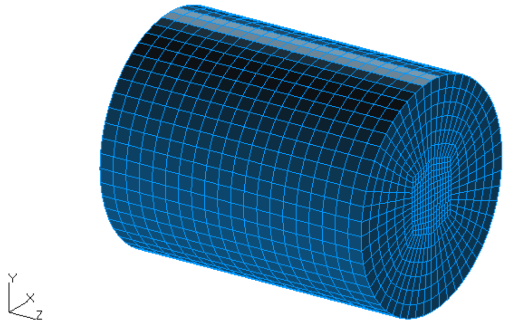

Fig. 9 Fluid cavity domain

B. *Finite Element Analysis*

The FEA (Finite Element Analysis) results in terms of surface vibration and sound pressure levels in the fluid cavity are reported in the following figures. In this investigation, the bare structure of the fuselage has been considered, i.e. without interiors and payload. The first three elastic modes of the structure are represented in Fig. 10-12. The mode shapes are congruent for both standard configuration that self-healing one: the difference between the two models has been contemplated only through the damping coefficient definition in the following frequency response analysis [4].

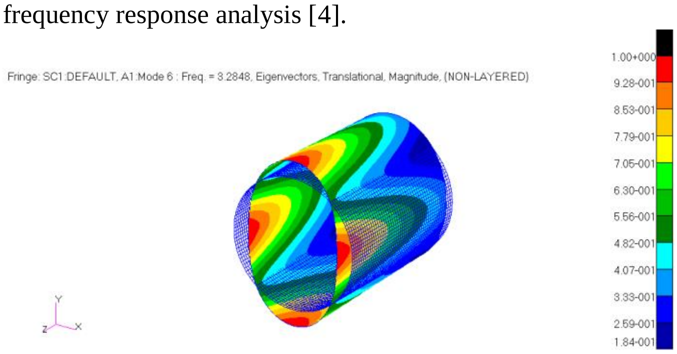

Fig. 10 Structural frame: first mode shape

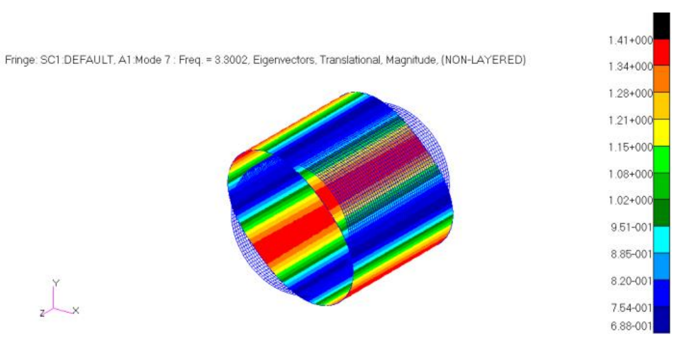

Fig. 11 Structural frame: second mode shape

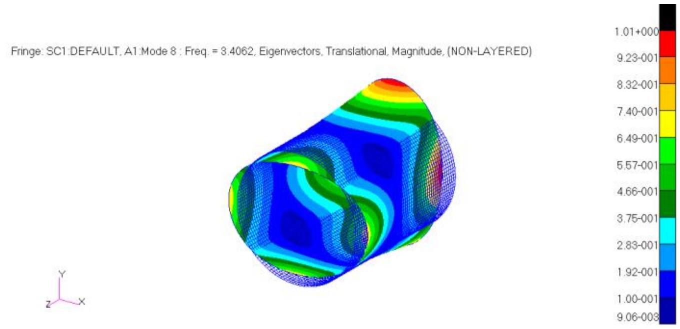

Fig. 12 Structural frame: third mode shape

For each configuration, the acoustic response by the air-structure interaction has been determined at every BPF. The average noise reduction achieved in the cabin thanks to the implementation of a more damped material is about 3 dB, Fig. 13. Such value will then be further reduced if the insulating interior treatments placed on the fuselage walls are considered.

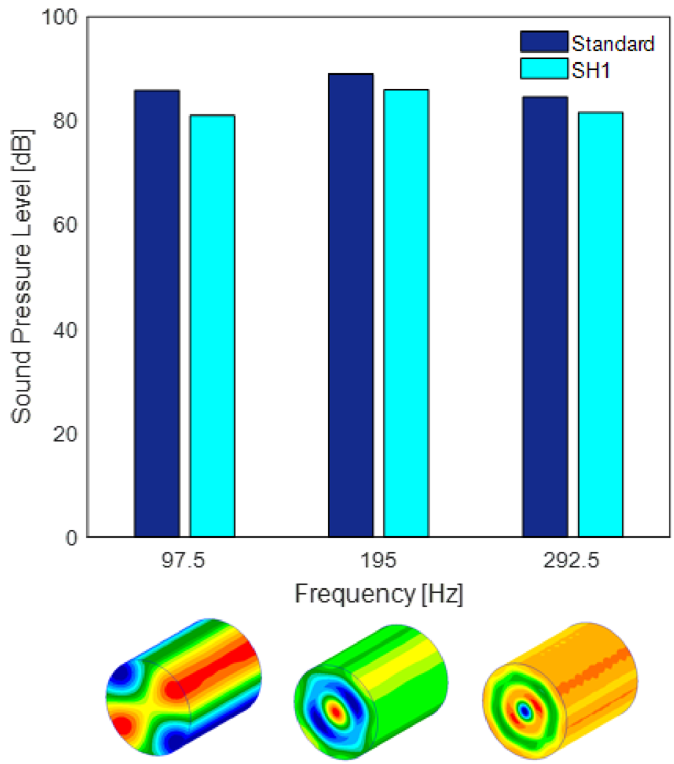

Fig. 13 BPF noise level reduction

Therefore, the dynamic test has been simulated on the numerical model, considering a white-noise pressure load applied along the bays in the same constraint condition in the spectral range [0; 200 Hz], Fig. 14.

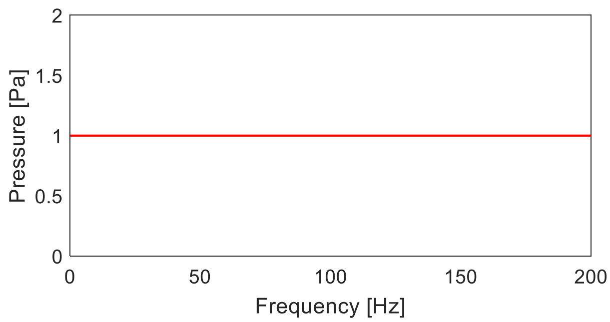

Fig. 14 White-noise signal

So both the acceleration and vibration velocity spectrum have been computed by means of modal frequency analysis, SOL 111 [5], Fig. 15-16. It is evident from the spectrograms the damping effect induced by the self-healing material SH1: the RMS (Root Mean Square) (1) rate as average of the squared values in a data set, indicates that the innovative composite treatment allows for reducing the surface vibration of approximately 50% compared to the standard laminate, Table III, Table IV.

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n}} \quad (1)$$

Table III Shell acceleration RMS rate

	Standard	**SH1**
RMS [m/s^2]	6.58*10^{-3}	2.98*10^{-3}

Table IV Shell velocity RMS rate

	Standard	**SH1**
RMS [m/s]	8.74*10^{-6}	5.05*10^{-6}

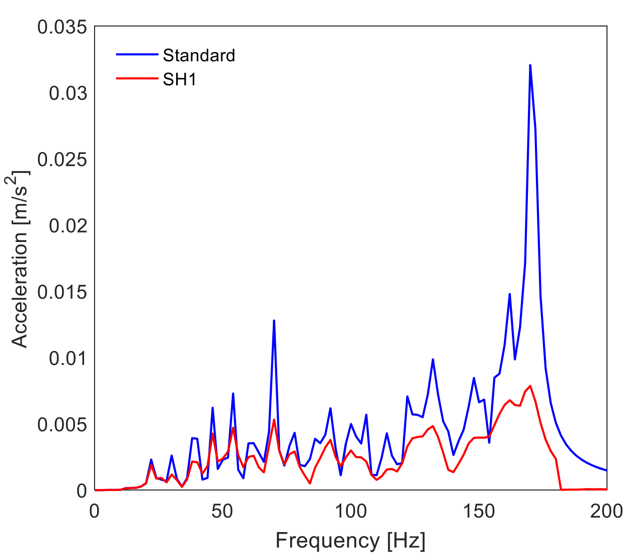

Fig. 15 Vibration acceleration spectrum, SOL 111

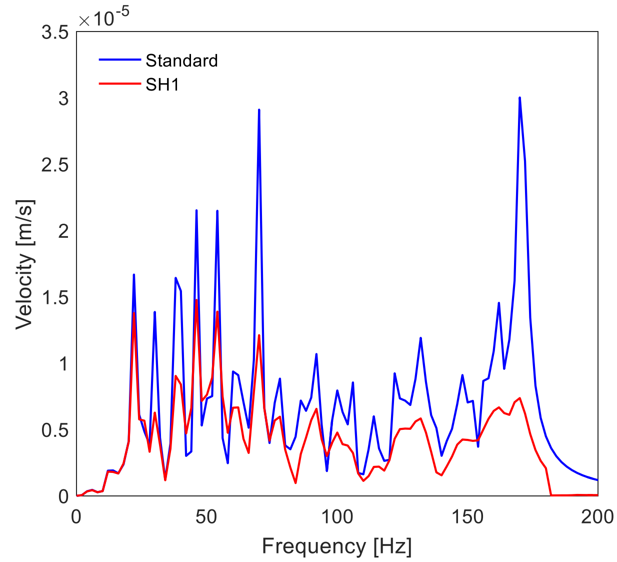

Fig. 16 Vibration velocity spectrum, SOL 111

C. *Radiated Power: Rayleigh Surface approach*

The main objective of this step is to develop a numerical expression for free-field acoustic power radiation due to harmonically vibrating source on the external skin. Acoustic power radiation can be defined as the rate of acoustic energy delivered by a source. Since the acoustic intensity is the acoustic power flow per unit area, the total acoustic power radiated by any source can be obtained by integrating the acoustic intensity over a reference surface. The acoustic power obtained as integration of the acoustic intensity over the surface can be expressed as a function of the vibrating pulsation ω (2):

$$\Pi_{RAD}(\omega) = \frac{1}{2} Re\left\{\int_S p_s u^* \, dS\right\} \quad (2)$$

where p_S is the surface pressure, and u^* is the complex conjugate of the surface vibration velocity (see [26-29]). Lord Rayleigh in 1896, was the first to study and define the structural relationship between velocity and pressure level produced by a plan radiator (3):

$$p(\omega, P) = \frac{j\omega^2 \rho_0}{2\pi c_0} \int_S \frac{e^{-jk|P-Q|}}{k|P-Q|} v(\omega, Q) dS \quad (3)$$

in which P, Q represent two points positioned on the vibrating surface, ρ_0 and c_0, respectively the medium density and the speed of the sound while k is the wave number of the acoustic disturbance (4):

$$k = \frac{\omega}{c_0} \quad (4)$$

In such framework, the fuselage skin has been defined as a radiating surface subjected also in this case to a spatially uniform harmonic pressure excitation in the range [0; 1000 Hz], consistent with the maximum elements size per wavelength. The FE model, set by means MSC Nastran® has been realized with too much detailed discretization level allowing to analyze with great accuracy the frequency response up to 1000 Hz. The finite element technique is widely applicable in the low-mid frequency range, while above this threshold statistical methods (SEA) are more appropriate due to the high modal density. The FE model has then been imported in Actran® for acoustic emission analysis in free-field, Fig. 17.

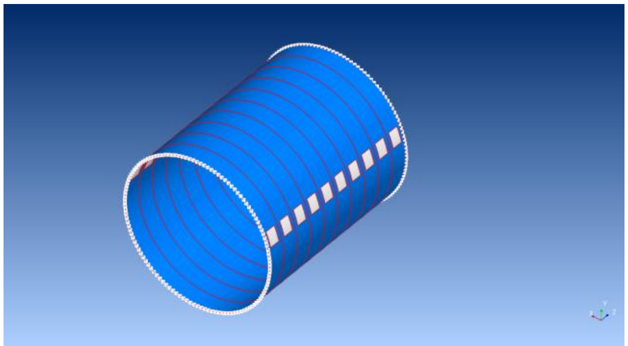

Fig. 17 Structural domain, Actran®

The Fig. 18 shows the trend of the radiated power in the narrow-band spectral domain: an average reduction of about 3 dB reduction of the smart laminate is observed also in this case validating that already provided by the previous simulations in MSC Nastran®.

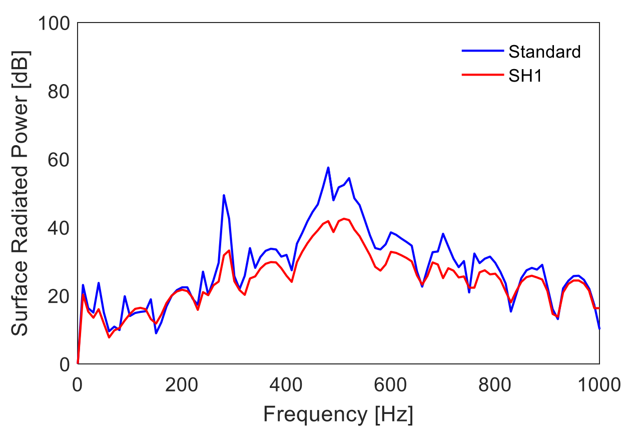

Fig. 18 Sound radiated power, radiating surface

IV. CONCLUSIONS

The prediction and reduction of aircraft interior noise are important considerations for conventional propeller aircraft now entering the commercial market as well as for aircraft currently being developed, such as the advanced turboprop. Consequently, the interior noise problem is receiving attention even during the first stages of the aircraft design process [23-25]. Vibrations topic is central in "low-noise" engineering field, especially in this research has been found an optimized solution to reduce the noise impact in the aircraft sector [30-31]. The present work has conducted a research to examine preliminary the adoption of innovative composite laminates with a self-repair treatment for aircraft primary structures, which may be as in this case the fuselage barrel. The self-healing design consists in dispersing microcapsules containing finely pulverized catalyst into the epoxy resin components [4]. These properties are very near to the requirements of structural materials and offer a very good solution among the analysed systems in the literature. These results can constitute a basis for improving self-healing function in aeronautic materials [2]. The damping enhanced performance of smart biomimetic solution reflects both into a lower acoustic noise transmitted inside the cabin and in a reduction of surface vibration, all over the investigated frequency range as outlined by the combined numerical simulation carried out within MSC Nastran® and Actran® environments [6], [16]. Further studies can be conducted on the original self-healing panel measuring the real acoustic emission by means of by non-invasive measurement techniques like the laser vibrometry or PU (pressure-velocity) probe in "near-field" conditions [32].

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