Smart materials for the internal vibro-acoustic performance improvement in turboprop aircraft

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Abstract: - The need for internal comfort improvement is becoming an increasingly important topic for both already operating aircraft that as a target for those still in the planning stage. Among the most relevant issues of many aeronautical industrial houses and not only, actually a recent target is representing by the research and the implementation of new passive and active solutions for noise and vibrations transmitted reduction. A valuable contribution in industrial research has been given by the composite materials, which use has grown significantly in recent years thanks to new manufacturing technologies, constituting an excellent alternative to metallic materials on several application fronts. Due to these peculiarities, composite materials are used for a long time as a result of experiments aimed at solving problems in different sectors and with different needs, including lately the aeronautical field especially thanks to the saving in weight combined high fatigue and corrosion resistance. The main purpose of this research activity is in particular focused on the prospective application of self-healing laminates in primary structural parts of an aircraft: the self-repairing strategy consists in dispersing catalyst active agents as microcapsules into the epoxy resin components during their manufacturing stage. Such innovative treatments, in addition to ensuring a better static performance by reducing the external interventions in the case of a crack, allow for dissipating the vibrational energy with a high damping level compared to a standard laminate as observed by previous experimental investigations. The reduced presence of mechanical joints and rivets, replaced mostly by special bonding makes an aeronautical composite structure globally less damped than a metal alloy frame. The present paper shows how the use of these features on the outer skin of a turboprop fuselage contributes to achieve a considerable reduction of the internal noise and especially the structural vibration level generated by the propeller source.

Key-Words: - Damping, internal noise, self-healing, smart material, turboprop.

1 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 [1]. 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 [2]. 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 [3]. Therefore, on the basis of the results achieved in the laboratory on simple specimens, a preliminary numerical model of an aircraft fuselage has been developed in order to assess the levels of noise and vibration generated by a typical propeller excitation load. The FE (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 as well as a vibration level abatement of 50% compared to the conventional laminate configuration.

3 Aeronautical Application

3.1 Numerical 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 [2]. 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. 1: a 2D mesh (CQUAD) with cross-ply orthotropic properties simulates the external coating (24 plies) having a thickness of 2 mm except for areas interested by the plexiglass windows, with thickness of 3 mm, Fig. 2. Moreover, the structure has been reinforced by Z-frames in aluminium (CBAR) [4]. The main characteristics of the numerical model are summarized in Table 1.

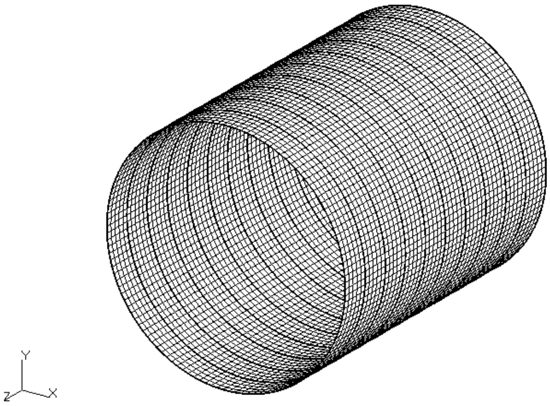

Fig. 1 Fuselage FE Model

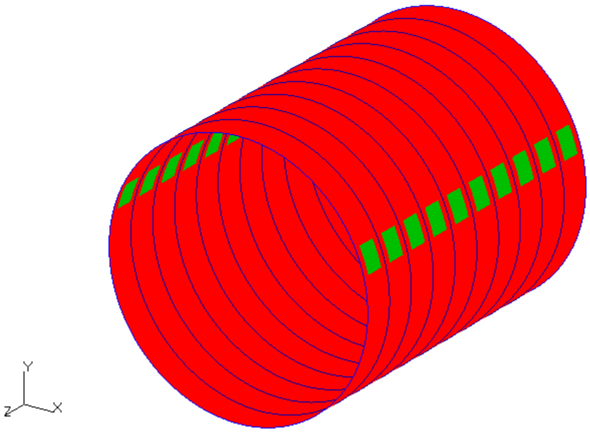

Fig. 2 FEM properties

Table 1 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. 3, 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. 4. All numerical analyses have performed assuming the extreme edges constrained in the rotation around the fuselage longitudinal 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 internal sound pressure level, Fig. 5 [4].

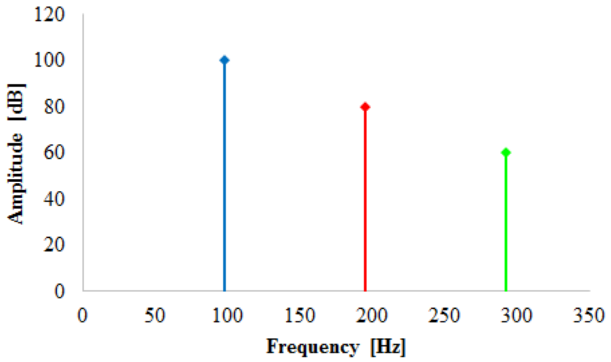

Fig. 3 Propeller tonal load, BPF

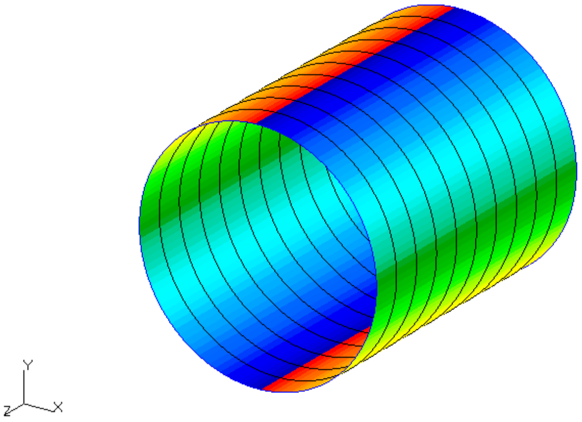

Fig. 4 External load application

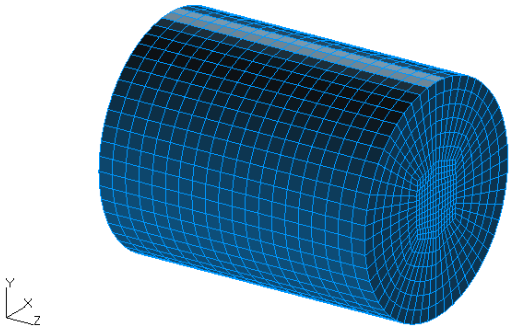

Fig. 5 Fluid cavity domain

3.2 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 two elastic modes of the structure are represented in Fig. 6-7. 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, Table 2 [3].

Table 2 Damping coefficients measurement

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

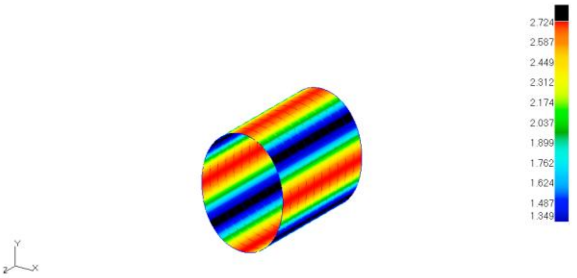

Fig. 6 First elastic mode shape

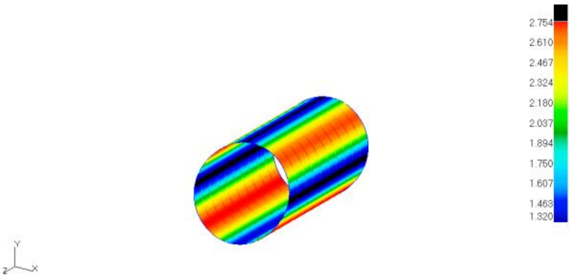

Fig. 7 Second elastic mode shape

For each configuration, the acoustic response has been determined at every BPF considering both the estimated damping in the time domain and in the spectral one, Fig. 8-9.

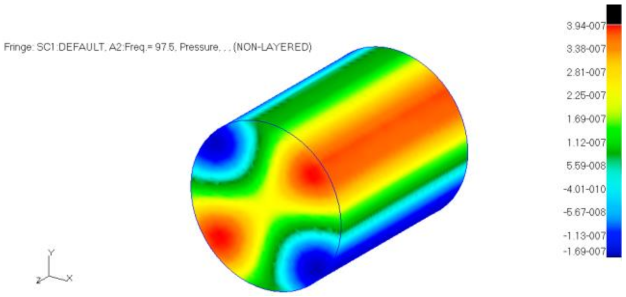

Fig. 8 Sound pressure, Standard, f = 97.5

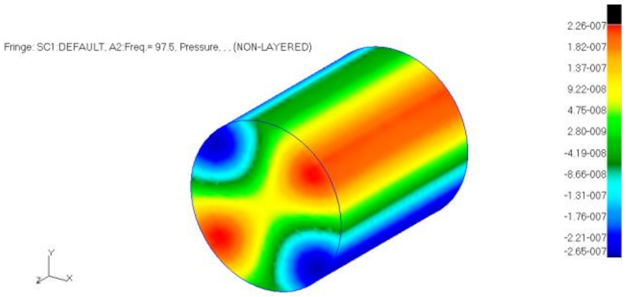

Fig. 9 Sound pressure, SH1, f = 97.5

The average noise reduction achieved in the cabin thanks to the implementation of a more damped material is up to 3 dB. This indicates that the cabin acoustic field has been considerably reduced with such treatment; this value will then be further reduced if the insulating interior treatments and trim panels placed on the fuselage walls are considered, Fig. 10.

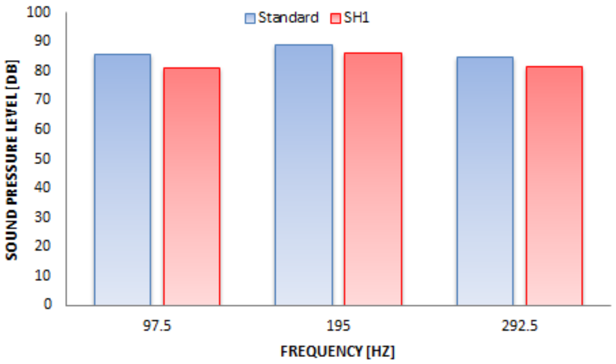

Fig. 10 Average Sound Pressure Level (SPL), BPF

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; 300 Hz]. So the transfer function g/N and the vibration speed spectrum have been computed by means of modal frequency analysis, SOL 111 [4], Fig. 11-12. The structural mode shape with very high level of vibration is represented in Fig. 13.

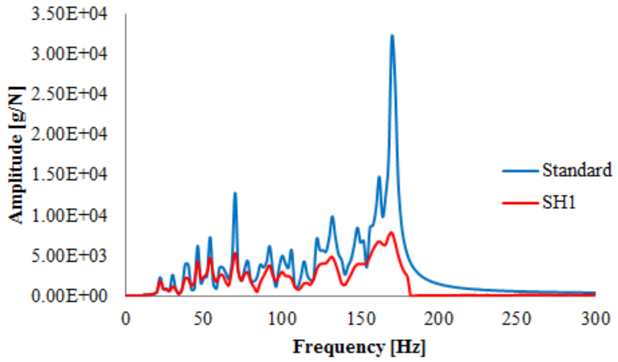

Fig. 11 Transfer Function (FRF), SOL 111

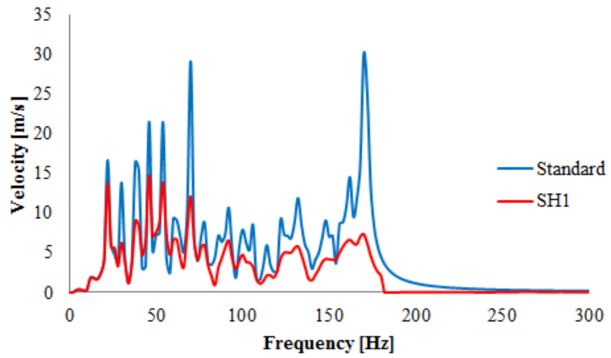

Fig. 12 Vibration velocity spectrum, SOL 111

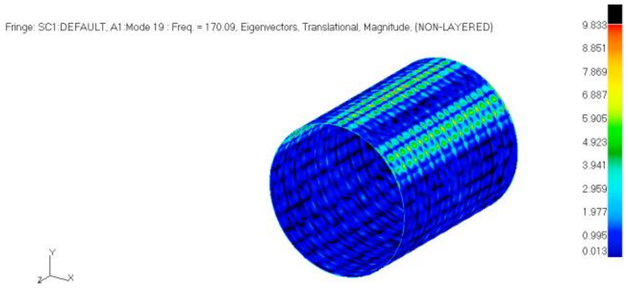

Fig. 13 Surface vibration level, f = 170 Hz

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 3.

$$RMS = \sqrt{\frac{g_1^2 + g_2^2 + \ldots + g_n^2}{n}} \qquad (1)$$

Table 3 Shell acceleration RMS rate

	Standard	SH1
RMS [g]	5.52*10^3	2.49*10^3

4 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 [14-16]. 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 [17]. 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 [3]. 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 [1]. 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 [5], [9]. Further studies can be conducted on the original self-healing panel measuring the real acoustic emission by means of non-invasive measurement techniques like the laser vibrometry or PU (pressure-velocity) probe in “near-field” conditions [18].

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