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ORIGINAL PAPER

Sound proofing and thermal properties of an innovative viscoelastic treatment for the turboprop aircraft fuselage

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Abstract

Low-resilience polyurethane foams including several additive constituents were synthesized to improve their vibro-acoustic performances, as well as the thermal insulation. viscoelastic polymer additive can attenuate vibrations and absorb sound energy. the vibro-acoustic properties of two innovative viscoelastic treatments fabricated with polyurethane foams are discussed in this paper using a typical aeronautical panel test setup. Since an aircraft insulation arrangement must provide both noise and thermal insulation for the specified operating conditions and expected thermal comfort of passengers, the thermal conductivity of the samples has been examined assuming a testing range between 20 °C (room temperature) and − 40 °C (cruise altitude). the results highlighted an optimal behavior of the novel viscoelastic foams in terms of both acoustic and thermal performance, offering a very interesting self-embedded solution with a good weight to performance ratio, compared to standard blanket composed by extra viscoelastic treatments.

Keywords Aircraft · Damping · Noise control · Thermal conductivity · Viscoelasticity

Abbreviations

ASTM	Americal Society for Testing and Materials
c	Speed of sound
CeSMA	Advanced Metrology Services Center
DIN	Deutsches Institut für Normung
E	Elastic modulus
EN	European standard
ζ	Damping
FE	Finite element
FEM	Finite element model
f_s	Schroeder frequency
η	Loss factor
G	Shear modulus
ISO	International Organization for Standardization
λ	Thermal conductivity
LDV	Laser doppler vibrometer
η	Loss factor
ODS	Operational deflection shape
PU	Polyurethane
PV	Pressure–velocity
PZT	Piezo-electric
ρ	Density
SPL	Sound pressure level
TL	Transmission loss
V	Acoustic volume
v_{ref}	Vibration velocity reference value

1 Introduction

The improvement of interior comfort is becoming an increasingly important aspect for passenger transportation vehicles, particularly for air transportation. Generally, an aircraft is affected by several noise sources, from the engine power unit to the broadband excitations related to the turbulent boundary layer. In this context, the leading industries in cooperation with research centers and universities are currently committed to develop innovative passive and active solutions for the internal noise as well as vibrations control. Such technological implications must represent an effective solution for both the aim of satisfying the design requirements and meet the current airworthiness regulations. In the last years, a constant pursuit in performance improvement has been demanded to the aeronautical products, mainly in reducing weight and optimizing manufacturing processes, hence in reducing the emissivity of polluting agents (NOx).

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The increasing interest towards the reduction of noise level for internal comfort improvement has also stimulated the development of novel sound absorption materials. Looking at the enhanced acoustic damping performance, lightweight porous materials such as polyurethane (PU) foams are commonly used in many aeronautical applications to absorb sound energy. These porous materials have been primarily used for thermal insulation and acoustic absorption, [1–3]. The authors are deeply involved in finding solutions for noise control issues, with particular reference to modern turboprop fuselages [4, 5]. In this framework, both active and passive solutions are investigated face this issue. The foams whose damping properties are going to be discussed in this paper belong to the viscoelastic materials class. Viscoelasticity is a property of certain types of materials whose behavior stands halfway between the viscous and the elastic ones. The using of these materials makes it difficult to experimentally characterize the damping level of a structure and its numerical modeling; however, damping is very important for noise and vibration control and for structural stability: the intent pursued by the authors in this paper, therefore, was to overcome these difficulties. Taking advantage of their particular vibration characteristics, low-resilience PU foams with viscoelastic properties have been designed specifically to have a high transmission loss (TL), assessing, moreover, the way they can be used effectively in aeronautical applications to enhance acoustic comfort always under a lightweight materials design concept, [6, 7]. Usually the sound damping materials used in aeronautical applications to insulate the cabin from external noise sources are the so-called blankets. They consist of an assembly of two materials, one with viscoelastic properties that reduce the structure vibration by muffling the structure-borne noise transmission and one with a relatively high acoustic absorption coefficient—such as fiberglass fabrics—that ensures a dampening of the airborne noise transmission, [8–14]. The foams that are going to be examined in this work offer the great advantage of combining both insulating properties into one material which is still lightweight, thus resulting easier to produce and highly efficient at the same time. The material formulation is polyurethane based: the manufacturing process involves first the formation of the PU matrix and then the injection of gas bubbles inside it. The gas bubbles create cavities (or cells) throughout the whole material, therefore, such injection has to be carefully monitored since if the bubbles are injected too fast, the whole foam could collapse, because of the matrix that is not stiff enough to hold the gas. Otherwise, if the injection process is slow, the foam could not grow correctly. In this study, the authors have also investigated the effect of density and thickness of two innovative PU foams on the sound absorption and thermal insulation characteristic. While in the literature the results concerning improved modal damping and thermal insulation of viscoelastic foams are very widespread, little has been found regarding sound transmission loss. Specifically, the low-resilience foams examined hereby are classified as the 65–30 (density-thickness) type and the 90–10. On the other hand, the classic blanket-like setup was obtained by assembling the foam-like polyester on the structure, with a viscoelastic sheet interface. Referencing to the case of a linear stiffened panel of a Tecnam P92 propeller aircraft, expressly designed and manufactured, the research activity was aimed to characterize some crucial properties of thermo-acoustic treatments, leading to conceive a new possible more compact package. For these objectives, several dynamic analyses allowed for estimating the low-frequency damping with particular attention to correlate the modal response to the acoustic emissivity of each configuration. The laser vibrometry proved to be a valid "noncontact" investigation technique as an alternative to the conventional modal procedures. It allowed for acquiring the operational deflection shapes (ODSs) of the structure with respective resonance frequencies. The sound intensity test procedure using a pressure–velocity (PV) probe has been performed to estimate the transmission loss of the panel in an anechoic chamber. An insulation arrangement must actually provide both noise and thermal insulation for the specified operating conditions and expected thermal comfort of passengers. The fiberglass blankets are traditionally used not just to suppress sound transmission into the aircraft interior but also to ensure thermal insulation. Finally, the authors considered really appropriate to assess also the thermal conductivity using an advanced test facility within the typical temperature envelope. The thermal conductivity of a polymeric foam depends mainly on three aspects: conductivity of gas state (gas bubble injection), conductivity of solid state and reciprocal thermal change among the cavities [15–20]. Although in a preliminary framework, the newly proposed materials are potentially not so inferior to standard solutions in terms of thermal insulation. The direct comparison of two viscoelastic foams is one of the main research themes opening the discussion in comparison with some data referred to high-class commercial solutions.

2 Damping treatments: passive control

2.1 Skin damping solution

The structure-borne noise due to the interaction of the fuselage with the external load excitation requires the installation of a damping treatment aimed to increase the levels of internal comfort. Add-on treatments are normally used to improve fuselage panels damping performance. They are based on the use of viscoelastic materials that have a high dissipation capacity and energy storage. Their behavior, due

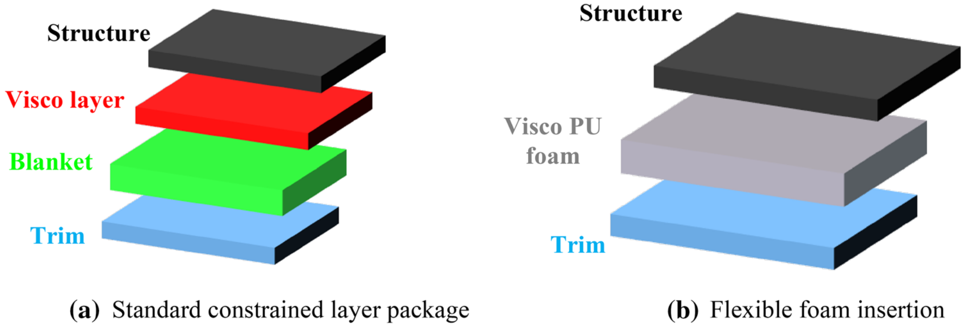


Fig. 1 Thermal and sound insulation packages

(a) Standard constrained layer package **(b)** Flexible foam insertion

to their nature, is described in terms of Elastic and Shear Complex Moduli:

$$E_C = E_1 + jE_2 = E_1(1 + j\eta) \tag{1}$$

$$G_C = G_1 + jG_2 = G_1(1 + j\eta) \tag{2}$$

$$\eta = \frac{E_2}{E_1} \tag{3}$$

where the real part E_1 represents Young's storage modulus, the elastic not dissipative part and determines material stiffness, and the imaginary part E_2 stands for the loss modulus representative of the capacity to dissipate energy, and gives a measure of it; η is named loss factor. A similar consideration can be made for Shear Modulus G. In this way, the usage of viscoelastic materials is driven by their high capacity to dissipate energy that translates into high values of loss factor η. The most common installation architecture comprises the constrained layer damping treatment, made by patches of viscoelastic and metallic layers laminates, attached to the structure to be damped (Fig. 1a) and covered on the other side by the insulation blankets and trim panel. The vibration of the structure in this case produces not only flexural stress in all layers, but also shear, mainly into the viscoelastic. Infact the metallic layer (constrainer layer) makes the viscoelastic to deform at shear: this mechanism is majorly responsible for energy dissipation, and then for damping. The performance of constrained layer damping treatment depends on its geometry and the type of constrained layer; generally is preferable to have as stiff layers as possible to maximize shear strain into the viscoelastic material. The package "structure—PU foam—trim panel" has been investigated in this research as valid solution able to replace the standard assembly, Fig. 1b.

The main properties of examined materials are listed in Table 1.

Table 1 Samples (300·× 150 mm^2) properties

Data	Foam 65–30	Foam 90–10	Viscoelastic sheet	Fiber blanket
Density, ρ (Kg/m^3)	65	90	1900	30
Thickness (mm)	30	10	1.3	60

2.2 Test article description

A practical way to understand the potential applicability of the materials conceived within this work is to test them on a real aeronautical structure. The above described improved treatments have been verified with respect to a fuselage panel (about 1.5 Kg) of Tecnam P92. This structure (baseline configuration) is made of three metallic main parts (Fig. 2):

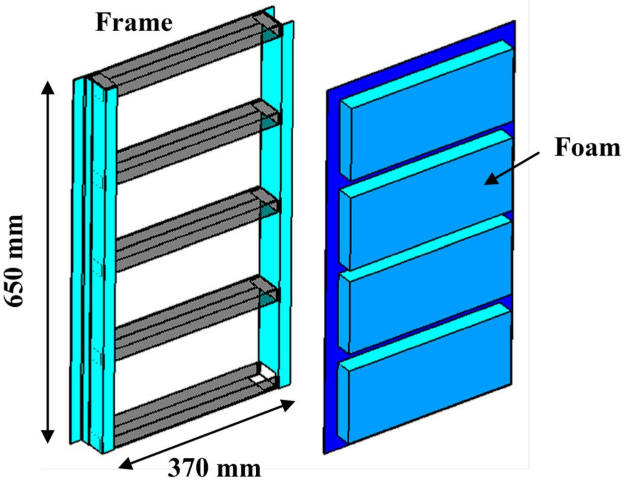


Fig. 2 Test article general overview

1. Skin—thick 1.5 mm;
2. 5 C-shape stringers—assuring a bending stiffening;
3. 2 Z-shape shear-ties—giving a longitudinal stiffening.

A FE (finite element) model of the test article has been realized adopting a 2D mesh: shell properties have been assigned both to the plate and to the stringers, Fig. 3. The results achieved by normal mode analysis within MSC Nastran® environment are well correlated with those

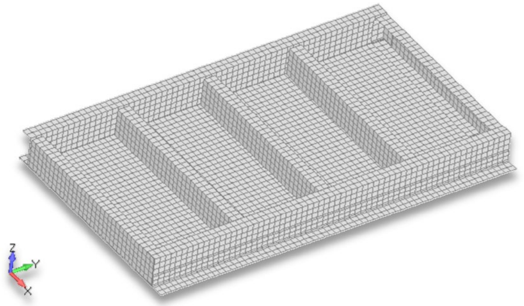


Fig. 3 FEM discretization of the reference panel

experimentally evaluated by hammer test, Fig. 4 and Table 2.

3 Vibro-acoustic performance assessment

3.1 Experimental modal set-up

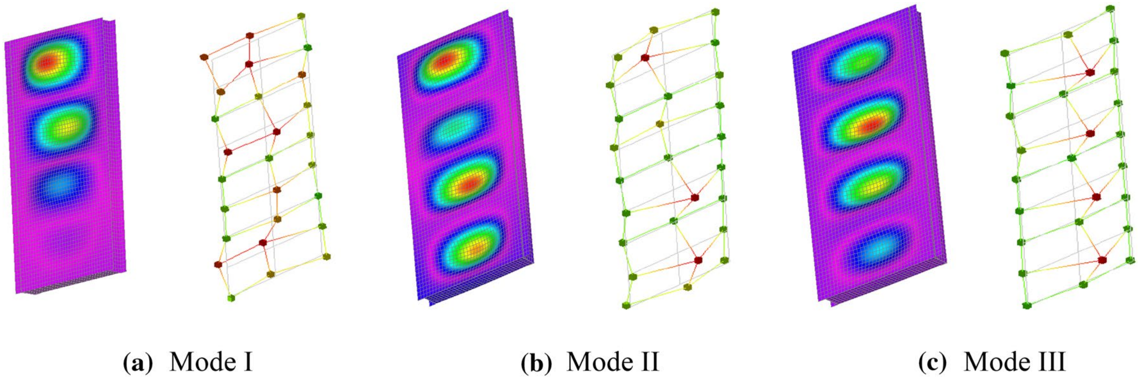
The vibro-acoustic tests were performed considering a free–free condition of the panel. The suspension by two soft springs to the frame of the test rig has been a suitable way to realize as many such boundary conditions as possible, Fig. 5. A first experimental campaign was fulfilled to estimate the dynamic performance as the modal damping, highlighting the effects of each dissipative treatment. A roving hammer-based technique was applied for these purposes: more precisely, both acceleration and acoustic signals at certain fixed stations have been recorded. The microphone has been placed at a fixed position of about 30 cm from the surface of the panel, Fig. 5a. In addition, the implementation of laser vibrometry has been useful for reconstructing the ODSs in a larger spectral bandwidth. In this case, a piezoelectric (PZT) actuator patch bonded on the internal skin has exerted a constant dynamic load (white noise) able to excite the structural modes up to 1 kHz, Fig. 5b.

Table 2 Modal frequency correlation

Mode	Test (Hz)	FEM (Hz)	Δ (Hz)	Δ (%)
I	140	143	3.0	2.14
II	170	178	8.0	4.71
III	200	212	12	6.00

The Fig. 6 illustrates the actual installation conditions of the specimens inside the panel cavities. The material samples are fully contained in the four bays bounded by the stringers. In “near-field” conditions, vibrational and acoustic transfer functions can be compared: the resonance response peaks appear in fact in both spectral signals, Fig. 7. The structural waves propagate as pressure waves too: in such a way, the comparison between the acceleration/force and pressure/force transfer functions can represent an index that defines the transformation of vibrational energy into acoustic disturbance at equal excitation level. For so much undamped systems such as a metallic structure ($\zeta \leq 1\%$), this coupling behavior turned out increasingly evident.

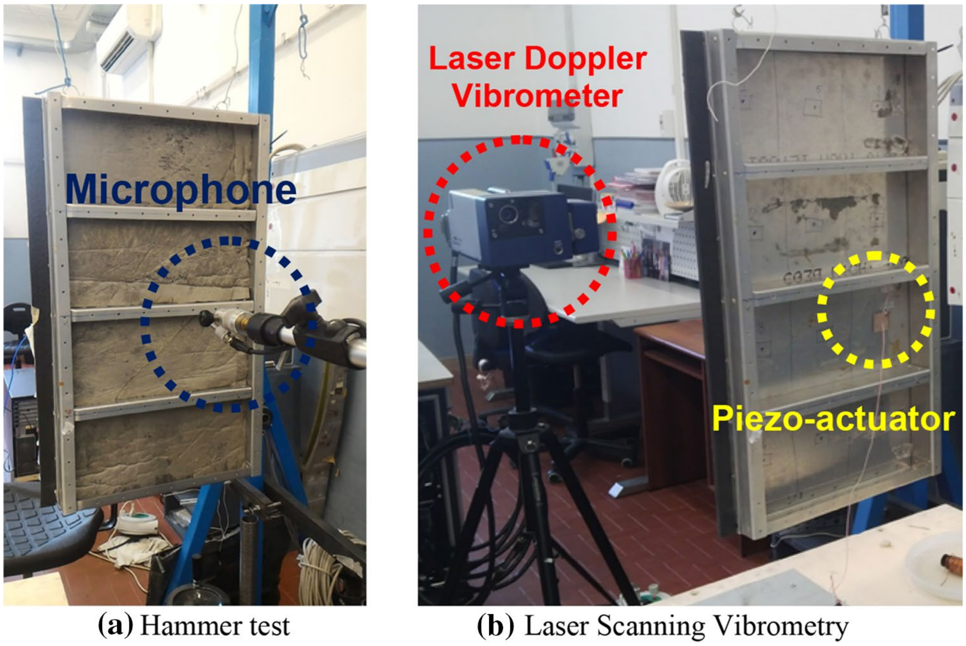
The experimental dynamic analysis allowed for estimating the damping ratio of all the participating modes in the analysed window: the following Fig. 8 shows the acceleration transfer function for each of the above-mentioned materials. High modal damping levels up to 12% are achievable by the viscoelastic foam 65–30 as well as by the standard solution, made up of the blanket with the viscoelastic layer. The graphs outline the results of the plain configuration for each case to better contrast the reduction effect due to the extra-damping of added materials. Furthermore, by representing both the acceleration and the pressure transfer functions (as in Fig. 9), it is possible to perceive in a preliminary stage how vibrational energy is actually transformed into perceived noise, mainly in the low-frequency region. It is really interesting to observe how the configuration with foam 65–30 exhibits, at least qualitatively, a trend almost similar to the full package configuration, comprising the viscoelastic



(a) Mode I **(b)** Mode II **(c)** Mode III

Fig. 4 Panel modal deformations

Fig. 5 Vibro-acoustic test set-up, baseline configuration



(a) Hammer test **(b)** Laser Scanning Vibrometry

(a) Foam 65-30 **(b)** Foam 90-10

(c) Viscoelastic sheet **(d)** Viscoelastic sheet + fiber

Fig. 6 Configurations analysed of materials

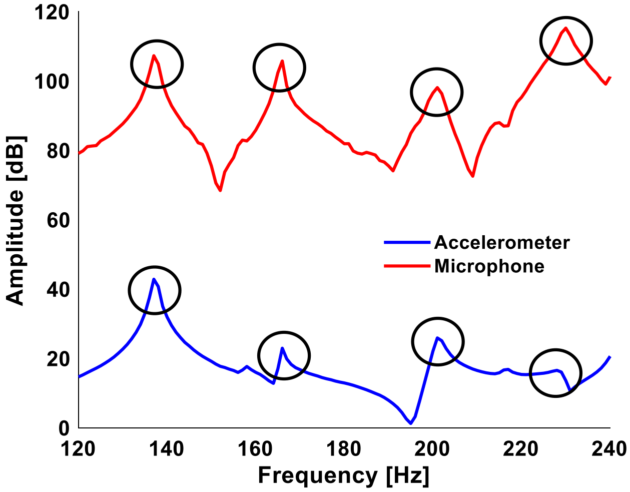
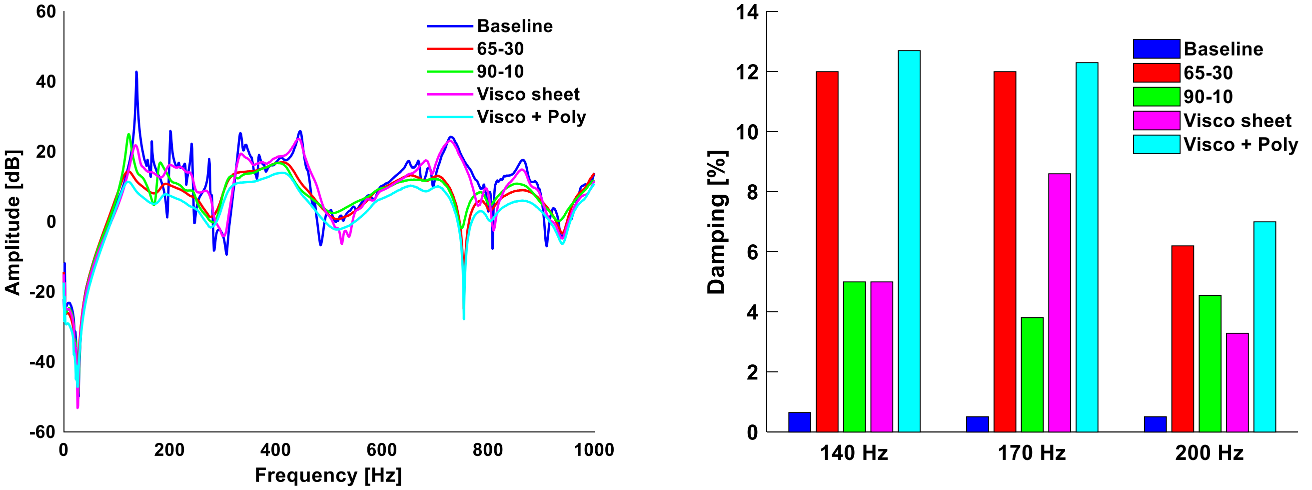


Fig. 7 Vibro-acoustic FRF (acceleration/force), (sound pressure/force), baseline configuration

sheet and the fiber. This result certainly constitutes a considerable advancement regarding the development of these new treatments considering also that such solution has a specific weight even lower than commercial standards. It has been conceived, as already introduced, for also guaranteeing thermal insulation. A lighter viscoelastic foam instead (i.e., 90–10, which corresponds to about 0.9 Kg/m^2) has less attenuation performance, as expected for the low-resilience materials.

On the other side, the laser vibrometry measurements allowed to detect the surface velocity spectra [21]. The calculation scheme considered is based on the studies widely dealt with in [22, 23]. The Laser Doppler Vibrometer (LDV) Polytec 400®, was placed 1.5 m away from the panel. The vibrating load was applied by means of a PZT transducer, which excited the structure following an appropriately amplified electrical signal (1:1000). The output results of the LDV was the vibration velocity magnitude, averaged on all the single-point measurements, identified on a grid representative of panel surface. A set of ODSs has been achieved



(a) FRF – acceleration/force **(b)** Modal damping

Fig. 8 Frequency response functions and damping assessment

within the spectral range (100 Hz; 1000 Hz), as shown in Fig. 10. During the laser scanning, the vibrating structure is divided in square elements where each one participates to the dynamic response. The mean squared vibration velocity has been obtained summing the modulus of the velocity at each virtual point. In Table 3, the overall value of squared vibration velocity level is indicated for all configurations.

4 Transmission loss assessment

4.1 Reverberating room: test set-up

Acoustic tests were carried out in order to define the transmission loss level of each dampening configuration. Normally, in order to achieve the reverberant sound field in the low frequency range, a larger room is needed. Such specialized infrastructure was not available for this study, thus the test was performed as follows: the sound source has been placed in an environment that guaranteed a reverberating acoustic field so that the whole panel surface was excited at the same sound pressure condition. A loudspeaker has been positioned to the bottom, inside a reverberating box (width: 400 mm; length: 400 mm height: 400 mm), Fig. 11.

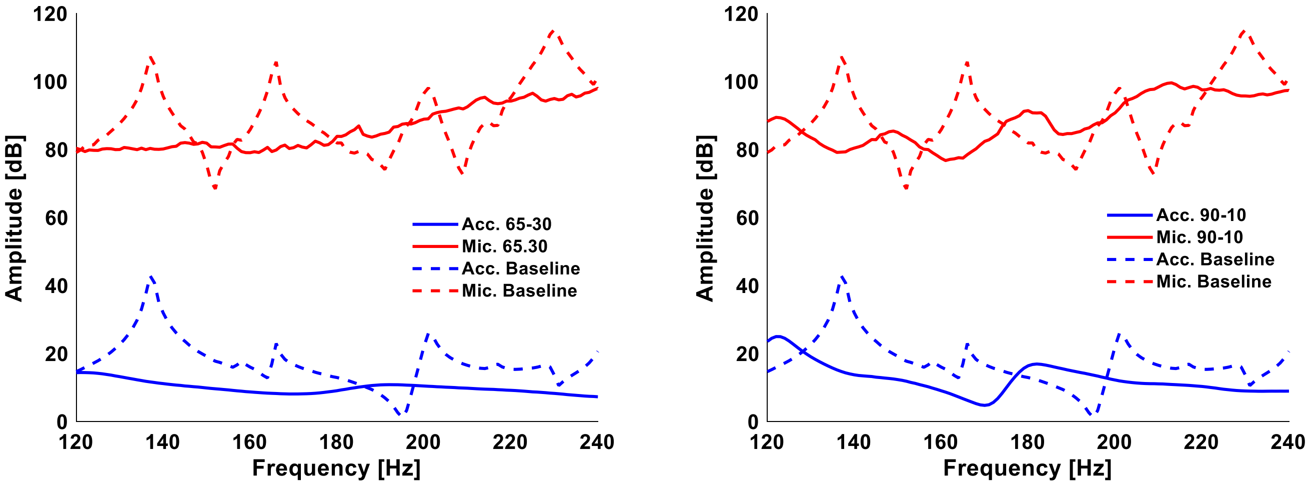
This experimental setup provides accurate TL results above the Schroeder frequency, which is expressed as:

$$f_s = \frac{c}{\sqrt[3]{\frac{V}{4}}} \tag{7}$$

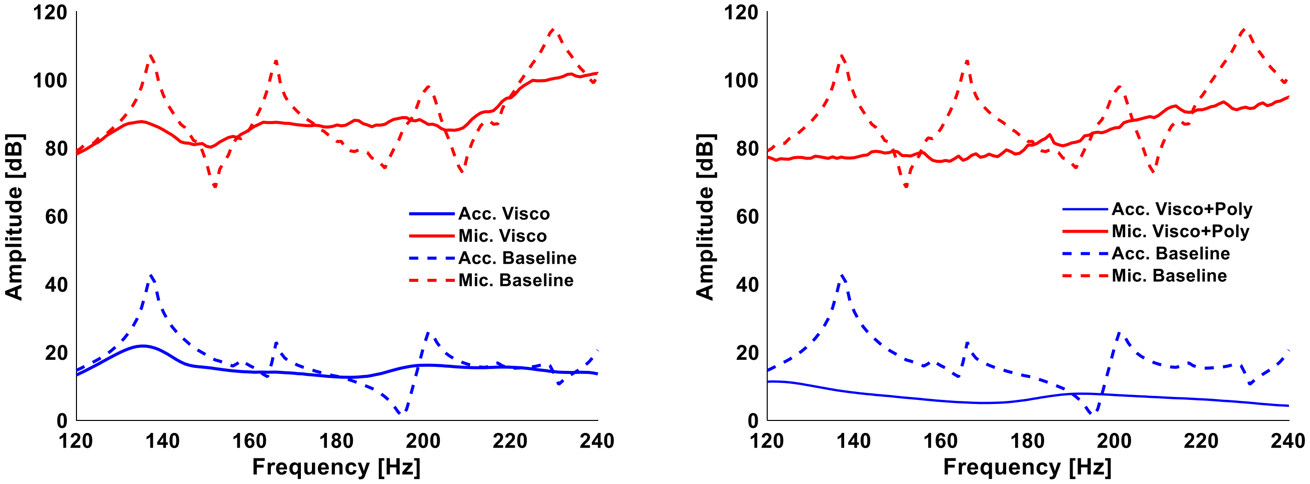
where c is the sound speed and V is the volume of the cubic box (0.064 m^3). This cut-off frequency has been added as a vertical line to the Fig. 12. Relying upon the estimated cross-over line, the Schroeder's frequency of the chamber is around 857.5 Hz (Fig. 12), which is not an ideal acoustic space in order to have effective data at lower frequencies. Anyway, this is intended here as a preliminary investigation just to assess the general trend of the sound performance.

4.2 Test results

A white noise signal has been used as input for the loudspeaker, obtaining a pressure excitation on the panel measured by the two microphones. All the Sound Pressure Level (SPL) measurements were arranged at a fixed distance from the panel, very close to this one in order to avoid all the environment influence. TL measurements have been therefore performed: Fig. 12 represents such results where a good agreement with the mass law trend may be considered. Looking at details of the experimental values, the coupled configuration involving than PU foam does not differ much from the "visco + poly" treatment. However, such conventional sidewall solution (0.15 Kg for each layer) involves a mass increase much higher, up to about 40%, compared to that obtainable thanks to an embedded viscoelastic foam (i.e. 0.087 Kg for 65–30 layer) as well as requiring additional installation costs. The acoustic measurements confirmed what has already been observed by the modal analysis: the behavior of the proposed foam, having a ratio of 65–30, is very close to the standard configuration, even considering medium–high frequency range.



(a) Foam 65-30 **(b)** Foam 90-10



(c) Viscoelastic sheet **(d)** Visco + Fiber material

Fig. 9 Vibro-acoustic responses, damping materials

5 Thermal insulation performance

Thermal insulation materials are specifically designed to reduce the heat flow. Viscoelastic foams may be included in the cellular insulators category unlike glass wools that belong to the class of fibrous ones. Thermal insulation properties of proposed foams have been assessed through the experimental evaluation of thermal conductivity in the temperature range from − 40 to + 20 °C. The test were performed at the CeSMA facility of the University "Federico II" (Fig. 13). The applicable standards ISO 8302, ASTM C177 or DIN EN 12667 [24] have been considered. The test machine used is the Netzsch GHP 456 Titan whose overall sketch and test coupon arrangement are reported in Figs. 13 and 14. The testing procedure is according to Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus. This equipment has a control unit comprising a sensing network of thermocouples that measure the contact temperature gradient and the changes in the sample temperature. The value of the thermal conductivity is characterized by the quantity of heat passing per unit of time per unit area at a temperature drop of 1 °C per unit length. It depends mainly on the medium's phase, temperature, density, molecular bonding, humidity and pressure.

The sample is placed between two heated plates set at different temperatures. The heat flow through the sample is measured by heat flux transducers. After reaching thermal equilibrium, the test is carried out. Only the sample center is used for analysis. The results achieved have been compared with some characteristic data of the aviation top class materials, Fig. 15. It is remarkable that the difference between commercial solutions having different density

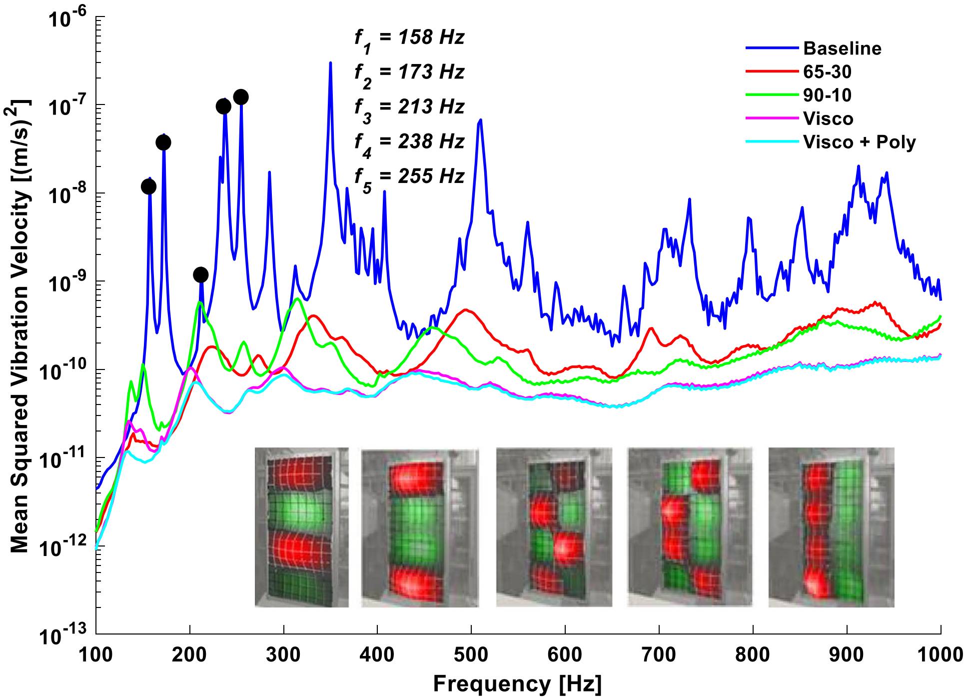
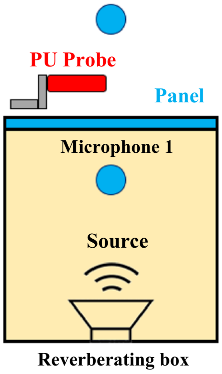


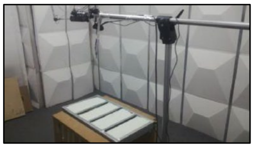
Fig. 10 Vibration response, laser vibrometry

Table 3 Overall value of vibration velocity

Configuration	Linear overall [(m/s)^2]	Overall [dB] ($v_{\mathrm{ref}} = 10^{-9}$ m/s)
Baseline	1.6E−06	102
Foam 65–30	5.9E−08	87.7
Foam 90–10	6.8E−08	88.3
Viscoelastic sheet	2.5E−08	84.0
Viscoelastic sheet + fiber	2.4E−08	83.7



(a) Experimental scheme



(b) External microphone installation

(c) PV Probe workstation

Fig. 11 Sound transmission experimental set-up

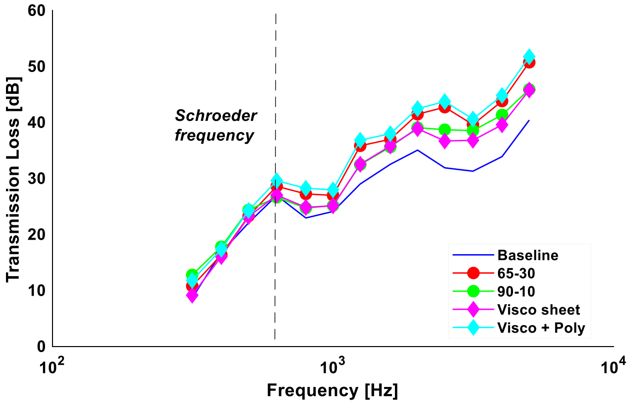


Fig. 12 Sound transmission loss spectrum

and thickness (Fiberglass 19.2–9.5, fiberglass 8–25.4 and melamine 10–54) and innovative treatments is not so large (Table 4).

6 Conclusions and further developments

Sound damping materials used in aeronautical applications to insulate the cabin from external noise sources are the so-called blankets that, in high performance configuration, consist of an assembly of two materials: one with viscoelastic properties that reduce the structure vibration by muffling the structure-borne noise transmission and one with a relatively high acoustic absorption coefficient—such as

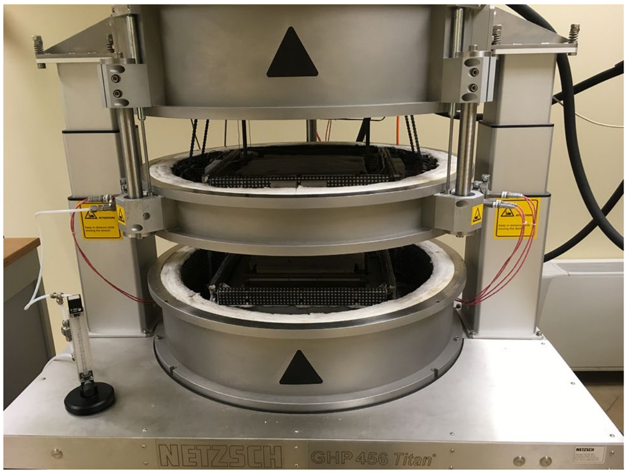


Fig. 13 Test facility for thermal analysis (Netzsch GHP 456 Titan)

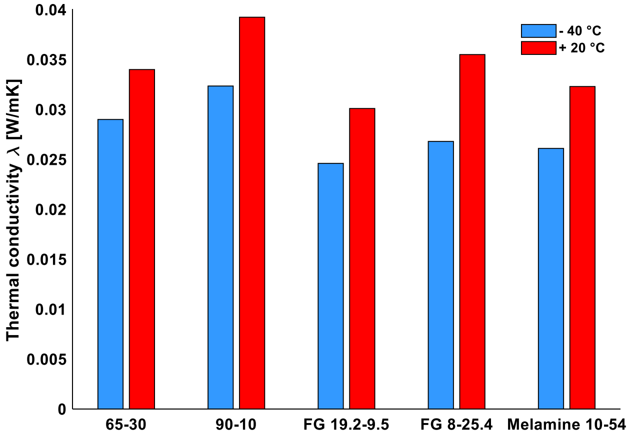
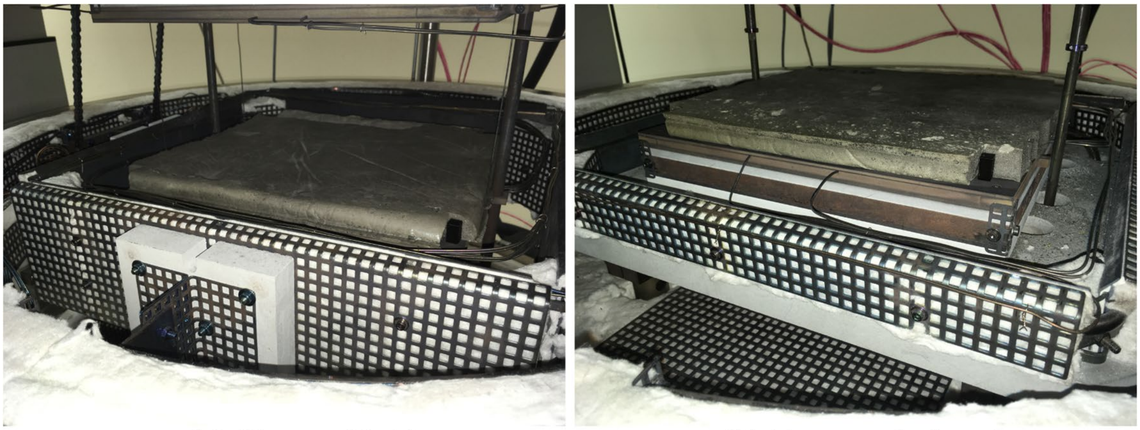


Fig. 15 Thermal conductivity: comparison among different materials

Table 4 Thermal conductivity summary

Material	$T = -40$ °C	$T = +20$ °C
Foam 65–30	0.0290	0.0340
Foam 90–10	0.0392	0.0324
Fiberglass 19.2–9.5	0.0246	0.0301
Fiberglass 8–25.4	0.0268	0.0355
Melamine 10–54	0.0261	0.0323

fiberglass fabrics—that ensures a dampening of the air-borne noise transmission. The viscoelastic foams assessed in this work offer the great advantage of combining both insulating properties into one sole material which is still light-weight, thus resulting easier to produce and highly efficient at the same time. The weight added by such treatments was lower than the configuration including the viscoelastic layer with the standard fiber material. The conventional package "viscoelastic sheet + fiber material" (0.15 Kg for each layer) involves a weight increase much higher, up to about 40%, compared to that achieved thanks to an embedded viscoelastic foam (i.e., 0.087 Kg for 65–30 layer), providing at the same time both low-frequency modal damping (up to 12%) and sound reduction as demonstrated by the test evidence. The increase of damping performance in fuselage skin, if opportunely optimized and improved, can lead to the condition of avoiding add-on treatment installation. This will lead to a significant weight saving on an entire fuselage, a more significant cost saving in terms of reduced part numbers to manage and highly reduced labor hours for the manual installation. The outcomes of the analysis carried out on a linear fuselage panel of a general aviation aircraft also indicate that the best compromise among vibration damping, thermal insulation and weight reduction can be



(a) Upper cold side **(b)** Focus on the hot plate

Fig. 14 Heating system

achieved by employing an embedded flexible viscoelastic foam rather than a heavier combination of viscoelastic sheet and standard fiber blanket. The thermal conductivity of the viscoelastic foams is very close to standard data referred to commercial solutions, especially at very low temperature (− 40 °C) typical of aircraft operating range. Such outcome is surely considerable for the cabin internal treatments, looking forward to potential implementation at industrial level. However, the density ratio of each foam should be further minimized to be fully comparable with fiberglass and others polyether polyurethane foams. Furthermore, next studies will be focused on the optimization of the topological layout of the PU foam, reducing the impact on the whole mass of the structure, yet leaving both the vibration level and thermal insulation unchanged.

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