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Acoustic Improvements of Aircraft Headrests Based on Electrospun Mats Evaluated Through Boundary Element Method

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Abstract: This work illustrates the development of passive noise control (PNC) improvements of aircraft headrests to enhance the acoustic comfort for passengers. Two PNC improvements were studied with the aim of reducing the noise perceived by passengers during flight. Two headrest configurations, with and without the lateral caps, and two different materials, a traditional foam and an innovative Silica/Polyvinylpyrrolidone (PVP) woven non-woven mat, were considered, and compared in terms of sound pressure level (SPL) perceived by passengers. Boundary element method (BEM) models were built up to evaluate the acoustic performances of different headrest configurations, varying in terms of shape and textile. A spherical distribution of monopole sources surrounding the headrests was considered as acoustic load, in such a way as to recreate a diffuse acoustic field simulating the cabin noise perceived by passengers during cruise conditions. The impact of the two PNC improvements was analyzed to envisage some general guidelines useful to design advanced headrests from the acoustic viewpoint.

Keywords: aircraft headrest; PNC; BEM; electro-spinning; PVP; Silica

1. Introduction

Noise or, more generally, unwanted sound, has become a growing problem for human health, leading to several adverse health effects, including hearing loss, sleep disturbance, and psychological harms. The accurate evaluation of noise generation and propagation has now become a key concern, especially in the areas in which the comfort for end users has become a turning point. Computing noise, taking into account the phenomena leading to its generation and transmission, is a challenging issue with several applications in different industrial sectors. In particular, acoustic numerical simulation has become an effective tool to evaluate upfront different design configurations for the purpose of comfort for aircraft passengers. The adoption of numerical simulation has allowed to strongly reduce the costs of experimental tests, especially in the fields for which such tests would present non-trivial complexities and/or huge costs.

An increasing interest of aerospace and automotive industries for the passengers' acoustic comfort [1] provided the framework in which these issues have acquired a prominent role.

Several approaches exist for such a kind of analyses, even though the most widely adopted seems to be the finite element method (FEM), thanks to its widespread field of application [2], supported by advanced implementations to improve the computational efficiency [3–5]. Deterministic methods, e.g., based on multibody simulation [6], boundary element method (BEM) [7], combined FEM-BEM [8,9], hybrid BEM/empirical approaches [10], and the fast multipole method (FMM)-BEM [11], are widely adopted to tackle vibration and acoustic assessments of complex structures.

In the field of linear acoustics, BEM is an important alternative to the more traditional methods, in particular for exterior problems, where the acoustic domain is so large, e.g., the open air or the ocean, that is acceptable to model it to be infinite in extent. Applying domain methods, such as FEM, to such a problem clearly requires some careful thought (an example of the infinite radiation condition application with FEM is available in [12]). Instead, it is more advantageous to use BEM for this kind of applications since only the surface mesh of the bodies is required, being the Sommerfeld radiation condition naturally satisfied at infinity (this is the condition at infinity for exterior problems that ensure that all scattered and radiated waves are outgoing) [13]. In this way, both preprocessing times and runtimes are reduced. As a matter of fact, BEM has become an established computational method for acoustics, widely adopted for noise calculations in the last decades [14].

FEM and BEM methods are usually applied for low/medium frequency ranges, whereas statistical energy analysis (SEA) is a methodology generally suitable for medium/high frequency ranges [15,16]. In the mid-frequency range, where deterministic calculations are costly and confidence intervals of SEA cannot be generally satisfied, hybrid FEM-SEA models represent a viable alternative [17,18].

Aircraft manufacturers are interested in decreasing the amount of noise in the fuselage by using new materials. In particular, they are interested in low-weight materials, which may help reducing the fuel consumption together with achieving lower noise levels. PNC (passive noise control) consists of adopting more performant design configurations and materials to reduce noise. These materials have the ability to reduce noise via dampening or lessening sound wave reflections, as sound energy is converted into heat dissipation. Efficient sound absorbents, such as porous materials, have the ability to prevent as many sound reflections as possible while also dissipating any unwanted sound entering the material. Thicker sound absorbers usually provide larger dissipation of air molecules vibrational energy because of the increased surface interaction area. However, thicker absorbers also increase the overall weight and dimensions of the structures. Today, most noise absorbers are porous membranes, cavities, perforated panels, and composite absorbers in the form of open- and closed-cell foams, fiberglass, cloth, mineral wool, acoustic ceiling tiles, and wood fibers. Also, metamaterials have been recently proposed for aircraft lining panels that seems to be promising in reducing the cabin noise [19].

An insight into the composite materials for passive sound absorption can be found in [20]. Within the field of advanced technologies for PNC, metamaterials [21,22], 3D printed components [23], and electrospun blankets [24,25] have recently attracted great attention for sound absorption. In fact, electrospinning is the only technique that nowadays can give micrometric or sub-micrometric fibers, that are, therefore, at least 10 times thinner than the traditional soundproofing materials. Blankets are typically produced as woven non-woven mats for which the thin fiber diameter gives a high surface-to-volume ratio, which is an ideal property for lightweight and porous materials. When a layer of microfibers is exposed to incident sound waves, the friction dissipation inside the micro-pores and the scattering of waves interacting with fibers dissipate the sound energy. Furthermore, the electrospun layers act as an acoustic resonance membrane: the membrane resonates at given frequencies, thus in turn deeply increasing the rate of sound energy conversion into thermal energy. The development of electrospun sound absorbers is very promising and very much needed, as there are increasingly higher demands on noise reduction in new products, especially for the aircraft and automotive industries.

Research is focusing on tests to assess the sound absorption properties of electrospun blankets [26,27]. Recently, silica particles were added to dimensionally stabilize the PVP mats during the cross-linking thermal treatment necessary to obtain water resistance and fire self-extinguishing behavior [28]. In fact, PVP blankets are obtained through a green electrospinning process that exploits solubility of the PVP polymer in ethanol [26,27]. The solubility in polar solvent, and therefore in water, is obviously a severe drawback in the blanket applications. This problem was overcome through a proper cross-linking heat treatment of the silica/PVP blankets [28]. The addition of silica also allows to obtain self-extinguishing materials that satisfy the severe Federal Acquisition Regulation.

The cabin noise reduction can be achieved by using high performance materials in combination with advanced computational approaches, such as BEM, to evaluate upfront the performances of several PNC implementations.

2. Problem Description

This work concerns the investigation of two PNC improvements on the Sound Pressure Level (SPL) measured at the passengers' ears during flight. One improvement is based on the choice of a peculiar shape of the headrests, whereas the second is based on the adoption of a PVP based electrospun mat to improve the absorbing performances of the headrest. Detailed information about these materials are available in [25–28] and are here briefly recalled.

In [28], the performances of an innovative electrospun mat made out of PVP plus silica inclusions was investigated from the acoustic standpoint. Silica inclusions were added to the PVP nanomaterial to obtain the water- and fire-resistant characteristics of the material, as requested by the aircraft industry. Several layers were overlapped as shown in Figure 1 to obtain the desired mass or thickness for the samples.

Figure 1. Layers of electrospun silica/PVP blanket.

Sound absorption coefficient at normal incidence α, defined as the ratio between the energy absorbed by the porous material and the incident energy of the sound wave, indicates the ability of the material to absorb sound energy in different frequency bands. α was measured by means of an acoustic impedance tube in the frequency range 200–1600 Hz according to the geometry of the adopted instrument (diameter and length of tube, microphones spacing) [25–27]. Data with reference to the Silica/Polyvinylpyrrolidone (PVP) woven non-woven mats were extracted from literature [25–27], whereas same impedance tube measurements were carried out specifically for the current investigation for the traditional material, i.e., a foam nowadays widely used in the aircraft industry. These data were then inserted in the numerical code to quantify how much noise reduction can be achieved with these innovative materials relative to the traditional ones.

3. BEM Simulations

The commercial code VA One [29] was selected for the numerical simulations. In particular, the BEM module of VA One was selected since the current modelling was referred to an exterior acoustic problem, in which a diffuse acoustic field was generated in the surrounding of an aircraft seat. This assumption allowed to strongly simplify the modelling strategy, even if the downside was that, assuming a fully reverberant aircraft cabin with the noise uniformly radiated to passengers, causes an increasing approximation in the lower part of the frequency range considered.

Figure 2 shows the initial CAD model of two aircraft seats, whereas Figure 3 shows the simplified seat modelling, comprising just headrest, backrest, and cushion. The remaining structural and non-structural seat parts, shown in Figure 2, were preliminarily considered in the simulations and subsequently removed, since they did not give any appreciable contribute to the SPL at passengers' ears. A simplified CAD model was adopted for the BEM modeling (Figure 4), where the headrest, differently from the remaining parts, is modelled with the new innovative material. Figure 4 also highlights the spherical data recovery surfaces, with a radius equal to 4 cm, in order to provide a spaced average of SPLs (rather than a less meaningful point assessment). The headrests were modelled in a flat and a folded configuration (Figures 3 and 4) and were alternatively adopted in the simplified modelling of the seat.

The considered frequency range was set up to 200–1600 Hz and represented by standard 1/3rd octave bands. BEM mesh comprised triangular surface linear elements with an element size equal to nearly 10 mm for the headrest and 20 mm for the remaining parts. Thus, at least 20 nodes per wavelength were adopted when considering the maximum frequency under analysis of 1.6 kHz. BEM fluid was air, with sound speed equal to 343 m/s, mass density equal to 1.21 kg/m^3, and a null damping loss factor.

The acoustic load was generated by means of a series of monopole sources, spherically distributed in the surrounding of a single seat, modeled in the abovementioned simplified way. Figure 5 shows an example of this loading conditions. All the monopole sources emitted a given sound pressure spectrum, calibrated so as to recreate a diffuse acoustic field, and having a sound pressure level representative of that existing in an aircraft cabin during flight [30]. Random phases were considered for all the sources.

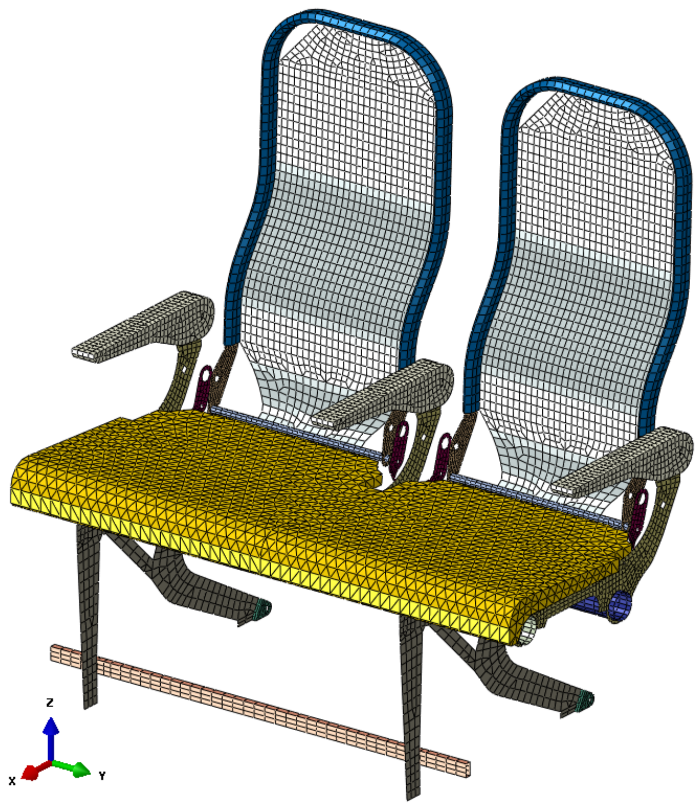

Figure 2. CAD model of two aircraft seats.

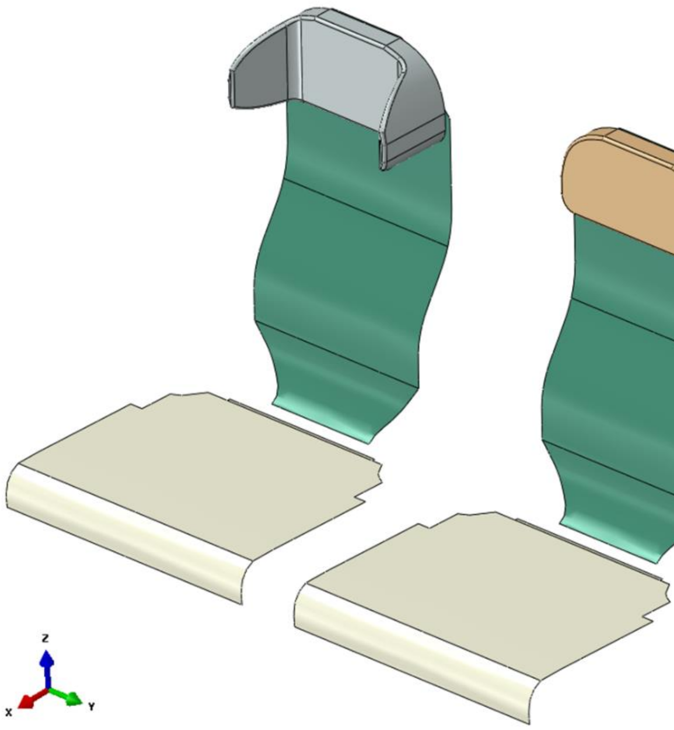

Figure 3. Simplified CAD models, considering both flat (**right**) and folded (**left**) headrest.

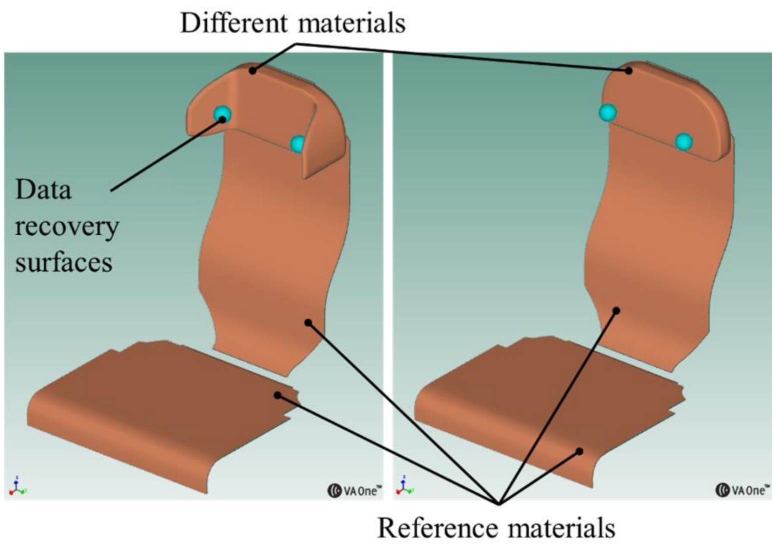

Figure 4. BEM models for the two headrest configurations.

Real and imaginary parts of acoustic impedance were inserted in the code. Impedance measurements were carried out in a Kundt's tube [25–27], thus assuming a perfectly normal incidence of sound waves: such condition rarely exists in mostly all the practical applications, but the related approximations were judged as acceptable for the current analyses.

PVP plus silica electrospun materials and foam were separately considered for the headrest surfaces, whereas the reference foam was considered for backrest and cushion surfaces. A total of six separate models were built up in order to calculate the SPL for two distinct headrest shapes and three distinct material combinations.

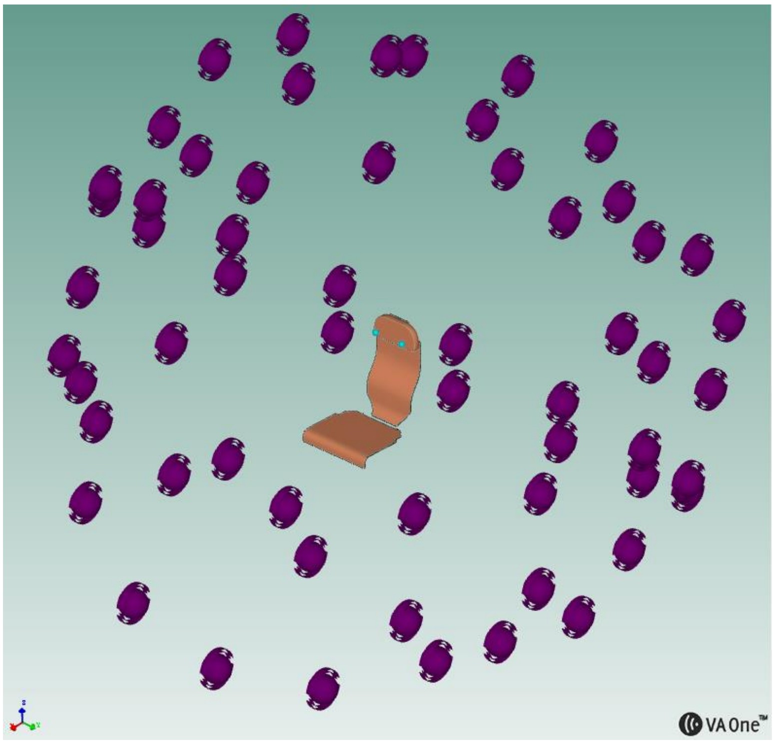

Figure 5. BEM loading conditions, with highlight of spatial monopole distribution.

4. Results and Discussion

Figure 6 shows the acoustic absorption coefficients available from literature [25–28] for two thicknesses of PVP plus silica inclusions samples. The figure also includes the absorbing coefficients, obtained by in house made measurements, for a foam widely adopted as material for an aircraft seat in two different masses. Mass and thickness of each material were reported in Table 1. The diameter of samples was equal to 10 cm for all materials. The simple foam was considered as the reference material to compare with the electrospun mats in the BEM simulations.

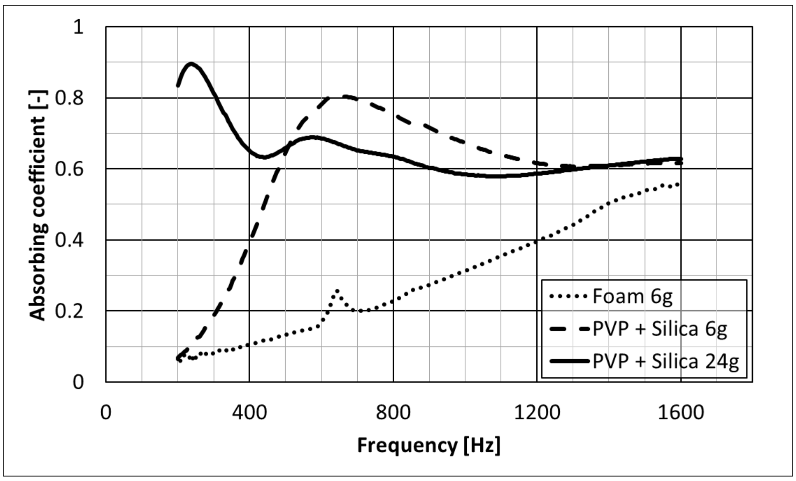

Figure 6. Absorbing coefficients for the considered materials.

Table 1. Masses and thicknesses for each considered material.

	Foam 6 g	PVP + Silica 6 g	PVP + Silica 24 g
Mass [g]	6	6	24
Thickness [mm]	12	11	45

It is worth noting that, in the frequency range up to 800 Hz, the acoustic absorption performance of traditional materials is generally weak, as for the "Foam" curve in Figure 7. On the other hand, from the literature [25–28], we know that electrospun mats presents remarkable sound absorption properties in the frequency range (400–1600 Hz), as well as a bell shaped α curve (Figure 6), in relation to a Helmholtz-type resonance, with a maximum (up to 0.9) (Figure 7). Such a peak of absorption shifts to lower frequencies as long as the number of piled disks increases [25–27]. Therefore, electrospun mats can also provide tunable sound absorbing properties since the absorbing peak frequency can be shifted with relatively low mass/thickness increments of the absorbing material [25–28]. Namely, electrospun materials can be designed in such a way to present the highest absorption properties at the frequency of the peak acoustic loads. Moreover, when adding silica particles, self-extinguishing and water-resistant blankets are obtained, preserving the aforementioned acoustic properties [28]. The samples showed also interesting thermal conductivity properties, useful for applications were also thermal insulation is required [28].

Results in terms of SPL measured at the data recovery spherical surfaces (Figure 5) are reported in Figure 8 across the considered frequency range, for the six different configurations of headrest shape and headrest material. Moreover, the OverAll SPLs are calculated for all the configurations and reported in Figure 8. SPLs and OASPLs were directly computed by the code (see Equations (1) and (2)).

$$SPL(dB) = 20\log_{10}\left(\frac{p_{RMS}}{p_{ref}}\right) \tag{1}$$

$$OASPL(dB) = 10\log_{10}\left(\sum_{i=1}^{n} 10^{\frac{SPL_i}{10}}\right) \tag{2}$$

In Equations (1) and (2), p_{RMS} is the effective acoustic pressure amplitude calculated as spaced average on the spherical data recovery surfaces (representative of passenger's ears in Figures 3 and 4, p_{ref} is the reference pressure level equals to 20 µPa, n is the number of considered bands.

The addition of lateral caps to the headrest turned out to be generally advantageous at frequencies higher than 800 Hz, whereas they were disadvantageous at lower frequencies, especially if used in combination with low absorbing materials. This can be explained considering that the lateral caps represented surfaces on which noise was scattered and directed towards the ears, so that, such enhanced reflections can only be compensated for by considering a highly absorbent covering material. In conclusion, the adoption of both strategies of headrest optimal shaping and high absorbing covering material can produce noise abatement, especially if used in combination rather than as standalone options.

High absorbing materials such as the electrospun mats can be used to reduce noise also at relatively low frequencies (even down to 300–400 Hz), where the classical soundproofing materials have poor performances [25–28]. In fact, by fine tuning the mass of the electrospun mats, it is possible to achieve the highest noise abatement at desired frequencies and this can reduce the noise level generated by the propellers, which fall in the range from 75 to 125 Hz for light aircraft and in the range from 160 to 250 Hz for the high speed turboprop [31]. Thus, the adoption of electrospun silica/PVP mats can lead to improvements of the internal acoustic comfort in this critical low frequency range.

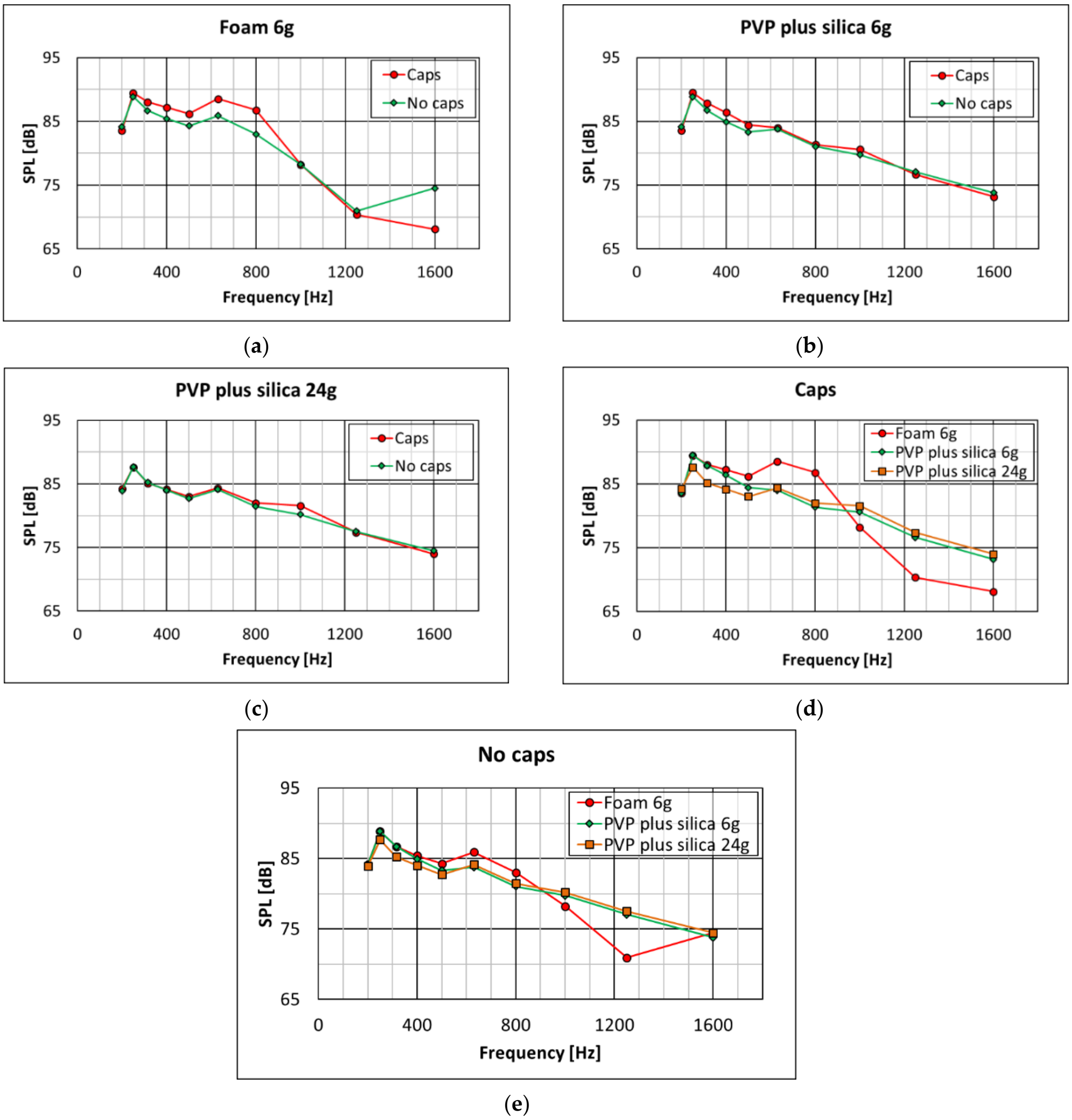

Figure 7. SPL vs. frequency spectra for the various headrest configurations with reference to the three considered materials (**a**–**c**) and to the two considered headrest's shapes (**d**–**e**).

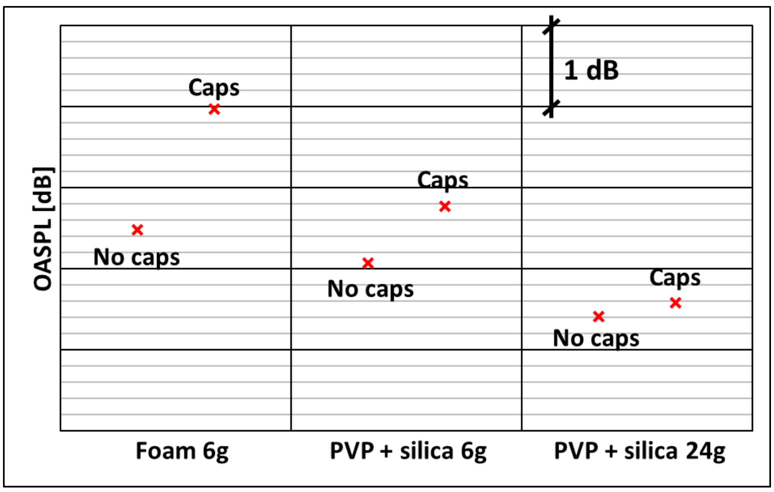

Figure 8. OASPL numerical outcomes for the various headrest configurations.

5. Conclusions

This work presented the development of two passive noise control (PNC) improvements of an aircraft headrest, useful to enhance its acoustic performances so as to improve passengers' acoustic comfort.

The PNC concepts were based on improvements to the headrest shape and its covering materials. Results were compared among all the considered configurations in terms of the sound pressure level (SPL) evaluated at the passengers' ears. The electrospun mat made of PVP plus silica inclusions was adopted as headrest covering material and turned out to be advantageous, and even more promising if used in combination with a proper headrest shape. In particular, the adoption of the electrospun silica/PVP material to a flat headrest shape turned out to be the best setup for an aircraft headrest in terms of noise abatement.

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