MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Passive Noise Control oriented design of aircraft headrests

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ABSTRACT

Propeller blades and Turbulent Boundary Layer (TBL) represent the main noise contributors of a turboprop aircraft, causing both passenger discomfort and community annoyance.

In this work, two technologies for Passive Noise Control (PNC) are numerically evaluated in terms of Sound Pressure Level (SPL) computed at passengers' ears. A technology is based on the shape optimization of the headrests for reducing the SPLs perceived by passengers, whereas a second technology is based on the adoption of nanofiber textiles to improve the absorbing performances of the headrests, in turn reducing the corresponding SPLs.

To this aim, a numerical SEA model of a turboprop aircraft fuselage has been used to predict the internal noise in the frequency range 200 – 4000 Hz. The TBL aero-acoustic load has been considered as the unique noise contributor in such frequency range. Then, the average SPL of the cavities inside the aircraft cabin has been carried out and then considered as input load around a single seat modelled with the Boundary Element Method (BEM). Finally, the latter BEM model has been used to evaluate different configurations of headrest shapes and headrest covering textiles in terms of their acoustic performances.

The work shows how an acoustic-oriented design of the aircraft headrests allows an average SPL reduction for passengers up to 3 dBA.

Keywords: Aircraft cabin, Passive Noise Control, Nanofiber textiles, BEM, SEA

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I-INCE Classification of Subject Number: 76

1. INTRODUCTION

This work is based on the development of two Passive Noise Control (PNC) technologies aiming to improve the acoustic comfort inside the aircraft cabin via numerical simulations.

For propeller-driven aircrafts, the dominant noise sources are the rotating fans and striking pistons, which create periodic low frequency loads on the fuselage at known Blade-Passage Frequencies (BPFs). For jet engine-driven aircrafts, including turbofan, turboprop and turbojet, the primary source of noise is the roar of the jet exhaust and the high-pitched noise generated by the engine's turbomachinery system, compressors, and engine blades [1, 2]. Moreover, the broadband character of the Turbulent Boundary Layer (TBL) flow on the fuselage outer surface during cruise results in interior noise, which dominates the overall Sound Pressure Level (SPL) and Speech Interference Level (SIL) [3] inside the aircraft, thus causing both passenger discomfort and community annoyance. Application of the BEM to problems in solids and structures can be found in [4-6] whereas some applications in aeronautic and railway fields can be found in [7-9]. In particular, in [7] a FEM-BEM modelling technique was used to predict the vibro-acoustic response of an aircraft fuselage. BEM was also used in [8] for the analysis of vibrations in a railroad track system induced by the passage of different types of trains, and in [9] for the acoustic scattering of large and complex aricraft configurations.

Two technologies for PNC are numerically evaluated to assess their performance for the reduction in terms of Sound Pressure Level (SPL) calculated at the passengers' ears. A technology is based on the shape optimization of the seats' headrests to reduce the SPLs perceived by passengers. The second technology is based on the adoption of high absorbing materials, i.e. nanofibrous textiles, to improve the absorbing performances of the headrests, thus in turn reducing the perceived SPLs.

To simplify the Design of Experiment (DoE), the current numerical simulations were performed considering the TBL aero-acoustic load as the unique noise contributor across the considered frequency range of 200 – 4000 Hz with 200 Hz constant bandwidth. The contribution of tonal noise, coming from the propellers' blades (BPFs) were considered negligible in the investigated frequency range.

The average SPL inside the cabin of the fuselage has been evaluated by means of the SEA module using the software VA One. The fuselage SEA model consists both the primary and secondary structures (stowage bins and seats). Such SEA modelling was presented in [10] and is here briefly reported. Consequently, the so-obtained average SPL inside the SEA acoustic cavity (i.e. the cabin) was considered as the acoustic load applied around a single seat modelled with the Boundary Element Method (BEM). Finally, the latter BEM model was then used to evaluate different configurations of headrest shapes and headrest covering textiles in terms of their acoustic performances.

The commercial code "VA One" [11] was selected for all the analyses.

2. NUMERICAL ANALYSES

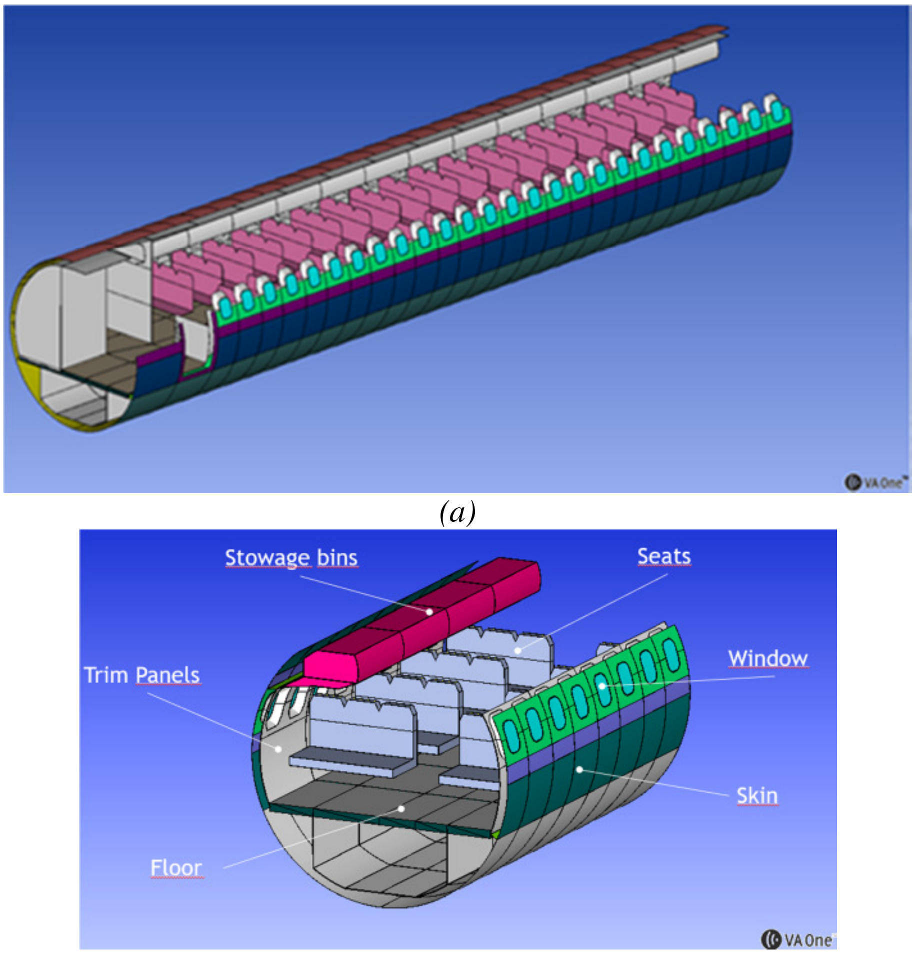
2.1 SEA modelling

A turboprop aircraft fuselage was modelled using the commercial code VA One through the SEA module (Fig. 1). Such fuselage comprised the fuselage trunk, the lavatory section, the stowage bins and the 90 seats (in 18 lines, each line comprising 3 plus 2 seats).

The internal arrangement of the acoustic cavities is shown in Figure 1; the internal cavity was divided in 3 main zones, namely head, leg and corridor cavities. In particular, the attention focused on the head cavity since the energy level measured in this volume was correlated to the SPL perceived by the passengers. The structure comprised the different materials with their isotropic or orthotropic properties, sandwich panels, etc. All the details can be found in [10].

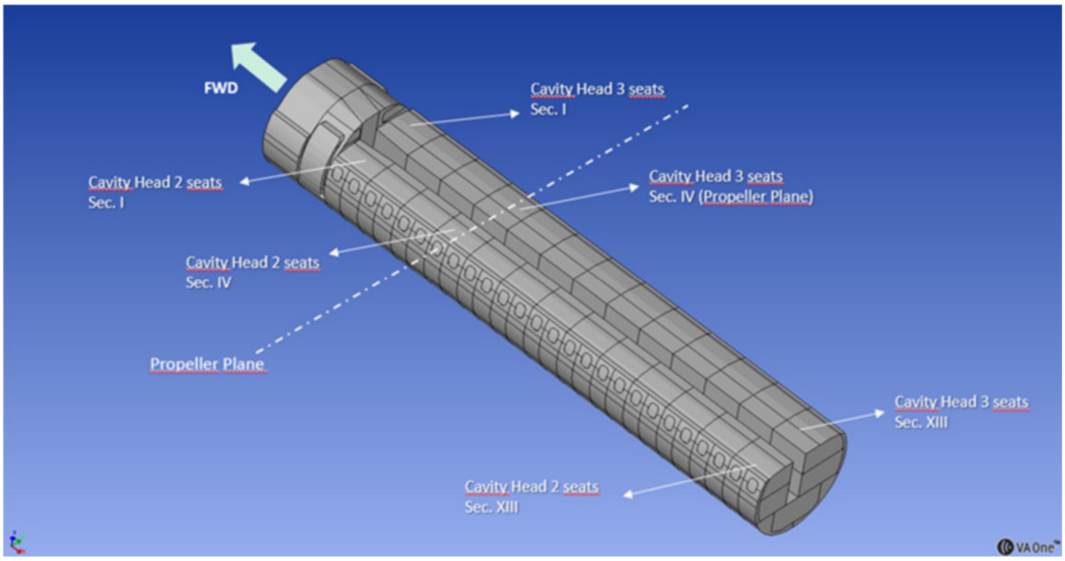
These simulations were used to predict the interior noise level considering the aircraft at cruising flight condition. These values partially characterized the TBL applied to each external panel of the model whereas the low frequency tonal loads coming from propellers were neglected.

Results in terms of SPL averaged among all the head cavities are reported in Fig. 2. Such data were the used as input load to apply on the BEM seat model.



(a)

(b)



(c)

Figure 1: (a) Isometric view of the fuselage trunk; (b) details on components; (c) . acoustic cavities distribution.

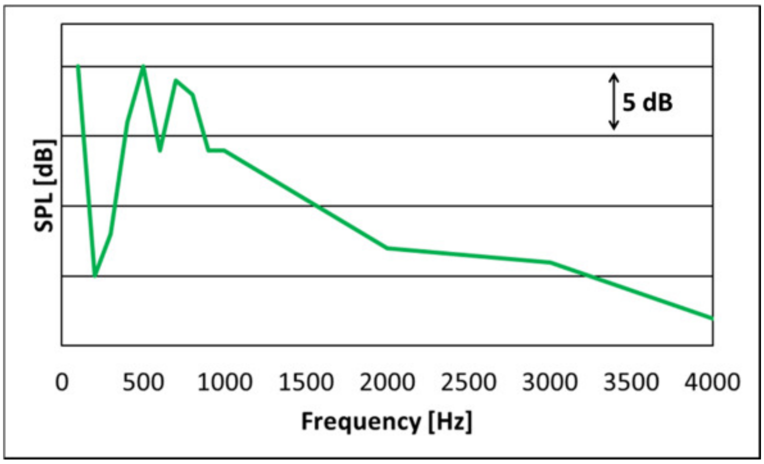


Figure 2: Sound Pressure Level [dB] averaged among the head cavities.

2.2 BEM modelling

The CAD model of the seat used for the acoustic assessments of the PNC technologies is shown in Fig. 3. Such CAD model was imported in VA One and a BEM model was created. Preliminary BEM analyses were aimed at reducing the size of the model to handle and the resulting BEM model is shown in Fig. 4. Such "baseline" model comprised only one seat with cushion, backrest and headrest; the whole supporting structure did not give any appreciable contribute to the SPL calculated at passengers' ears height. This simplification allowed to reduce the computational burden introducing a small element of approximation.

The final BEM model comprised nearly 7150 linear boundary elements with an average size equal to 0.014 m, thus 6 elements per wavelength were used at maximum frequency of 4 kHz. The BEM fluid was air with bulk modulus equal to 142.355 kPa and mass density equal to 1.21 kg/m^3.

Two different shapes for the headrest were considered on such baseline model (Fig. 5); such shapes were representative of the smallest and largest headrest that were envisaged for such a headrest shape optimization process. Moreover, various combinations of headrest shapes as well as headrest covering textiles were considered as part of the DoE. For all the simulations, the same data recovery surfaces (shown in azure in all the Figs. 4-6) were considered as the areas on which the SPLs were output. Such SPLs were then compared among the various configurations allowing to realise how much the impact of different geometries and materials would be on the passengers' perceived noise.

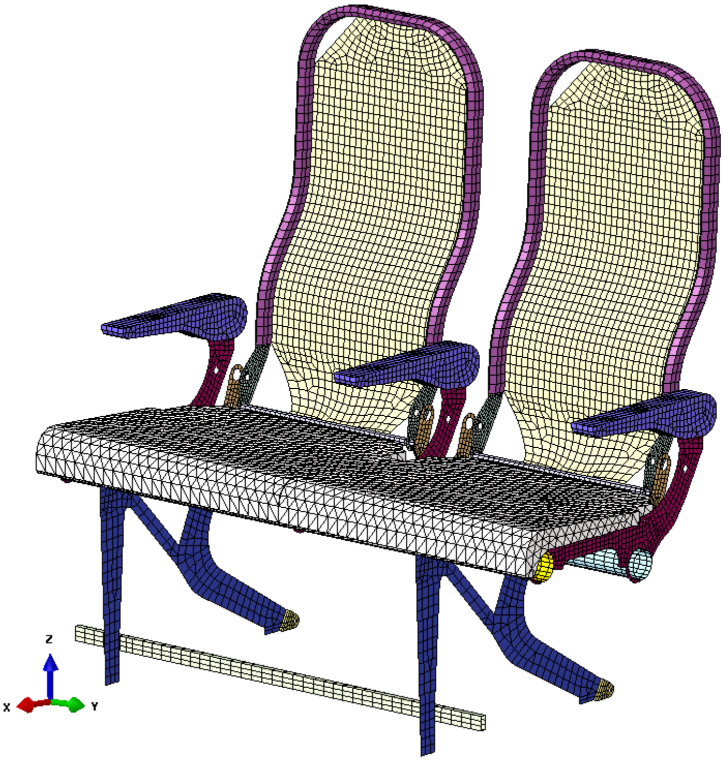


Figure 3: CAD model of two seats.

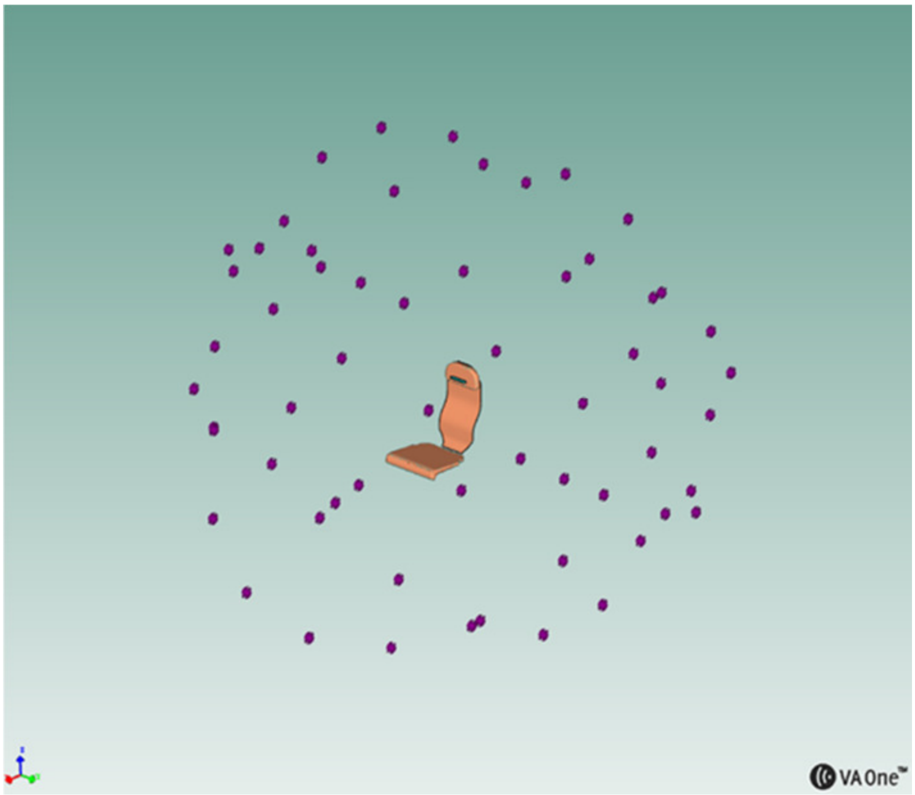
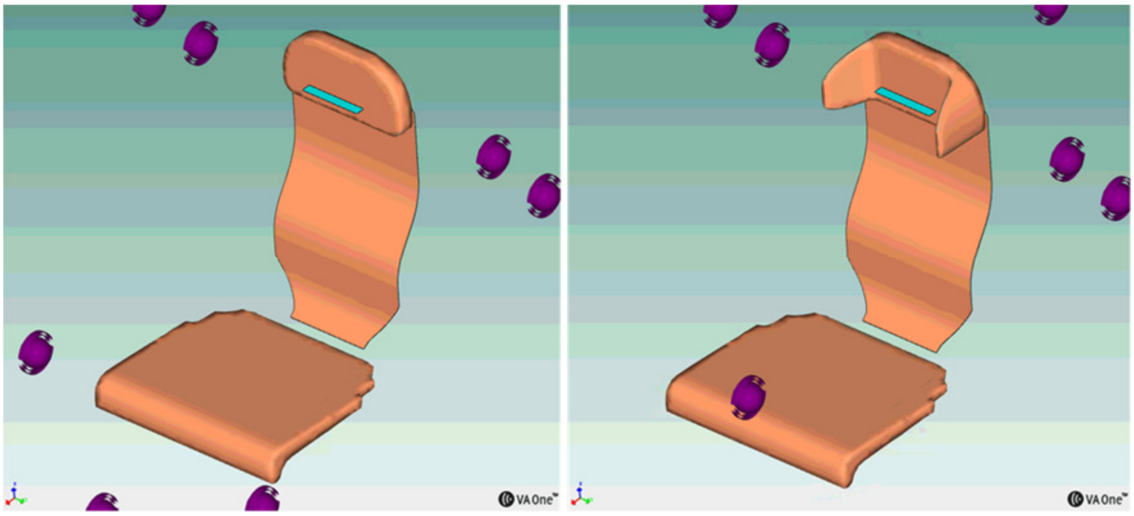


Figure 4: Monopole spherical distribution surrounding a simplified seat.



(a) *(b)*

Figure 5: Simplified seat modelling, with headrest (a) without caps or (b) with caps; data recovery surfaces to output the SPLs at the height of the passengers' heads.

The headrest was considered as covered by different textiles: a traditional one termed "reference" and two new-generation nanofibrous textiles [12-13], whereas the backrest and cushion were covered with the reference textile for all the analyses. Such impedance data in terms of real and imaginary parts are shown in Fig. 7. All the material impedances were obtained experimentally by means of a Kundt's tube. Such data were measured in the frequency range 160 – 1600 Hz and, subsequently, the experimental measurements were extrapolated up to the 4 kHz considered in this work [12-13]. Fig. 7 presents the impedance data in terms of specific resistance and reactance for three different textiles, namely "PVP6g", "PVP24g" and the reference material "RedTex". In

Fig. 7, “RedTex” refers to a common textile used in the aircraft industry whereas the two PVP are two nanofibrous textiles made of Polyvinylpyrrolidone (6g and 24g refer to the weights of the samples measured experimentally [12-13]).

All the BEM simulations were performed across a frequency domain of 200 ÷ 4000 Hz, with a 200 Hz constant bandwidth. All the analyses were based onto several uncorrelated monopole sources located at equal distance of 2 m from the centre of the backrest’s surface. Such sources were positioned spherically so as to reproduce a diffuse acoustic field that surrounds the seats. All the monopoles were set up in such a way to generate a pressure distribution providing a SPL at the data recovery surfaces similar to that calculated by the full SEA modelling of the fuselage (Fig. 2; §2.1; i.e. the spatial average SPL calculated by SEA was reproduced via a spherical distribution of monopoles).

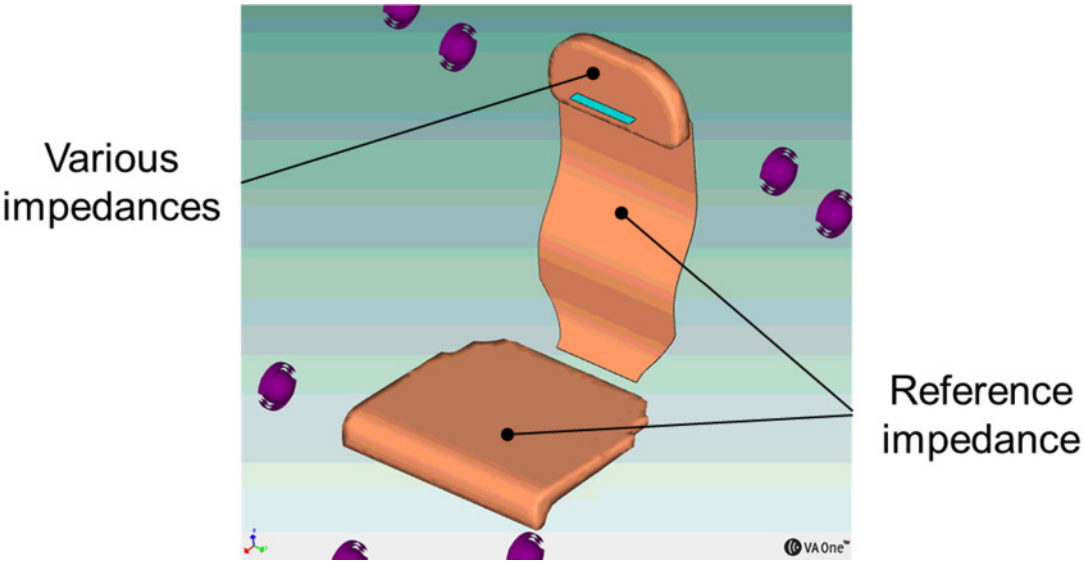


Figure 6: Description of the impedances on the simplified seat.

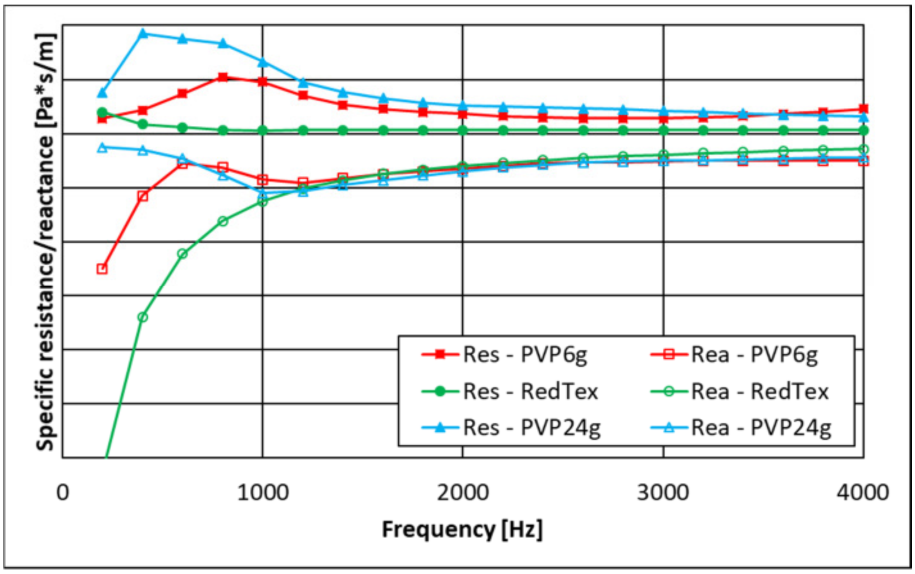


Figure 7: Impedance data used in the BEM analyses;

3. RESULTS

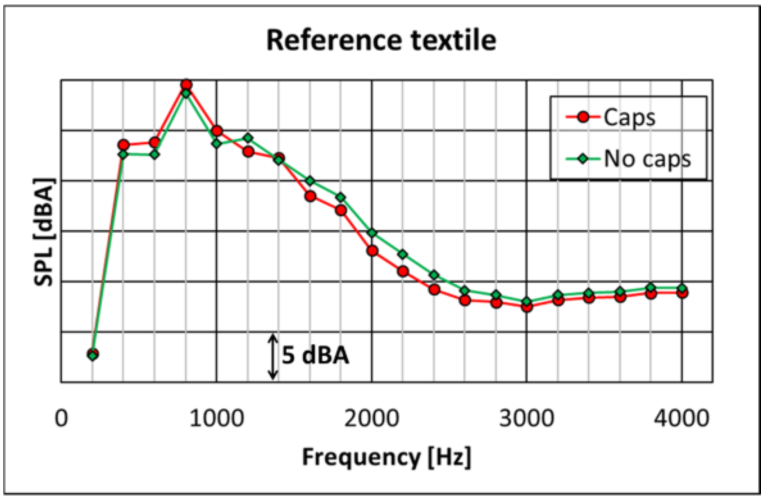
Results in terms of SPL were calculated on the data recovery surfaces (Figs. 4-6), so as to represent the average SPL that the passenger perceives as cabin interior noise. Fig. 8 shows the aforementioned SPL values vs. various configurations of headrest shape and headrest covering textile.

Results are then summarised in Fig. 9 in terms of SIL3 parameter (Eq. 1; Fig. 9a) and average SPL (Eq. 2; Fig. 9b). SIL3 values were calculated by summing the pressure for the octave bands at 1 kHz, 2 kHz and 4 kHz (Eq. 1), whereas the average SPLs were calculated across the 20 bandwidths in the range 200 Hz – 4000 Hz (Eq. 2).

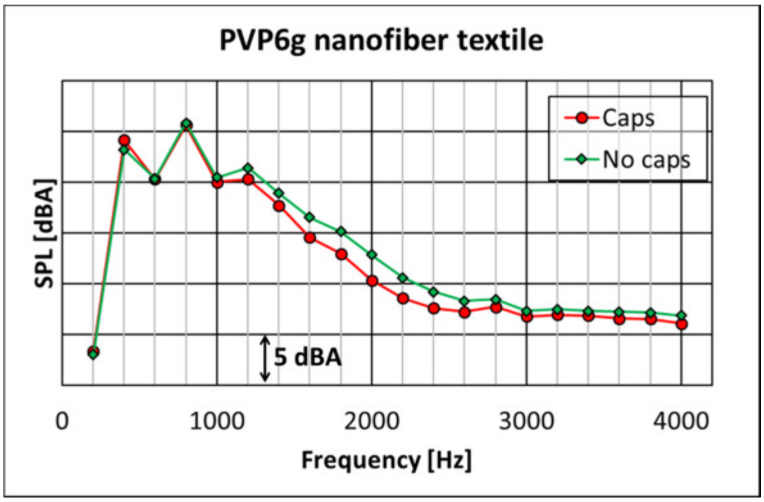
$$SIL3 = 10\,\mathrm{Log}_{10}\left(\sum_{i}^{3} 10^{\frac{SPL_i}{10}}\right) \tag{1}$$

$$Avg.SPL = 10\,\mathrm{Log}_{10}\left(\frac{1}{20}\sum_{i}^{20} 10^{\frac{SPL_i}{10}}\right) \tag{2}$$

Such results demonstrated that using both, a headrest and an appropriate absorbing material, it was possible to reduce the SPL values perceived by the passengers. In particular, the usage of a headrest with lateral caps seemed to provide significant advantages only when used in combination with high absorbing covering textiles such as the here considered nanofibrous textiles.



(a)



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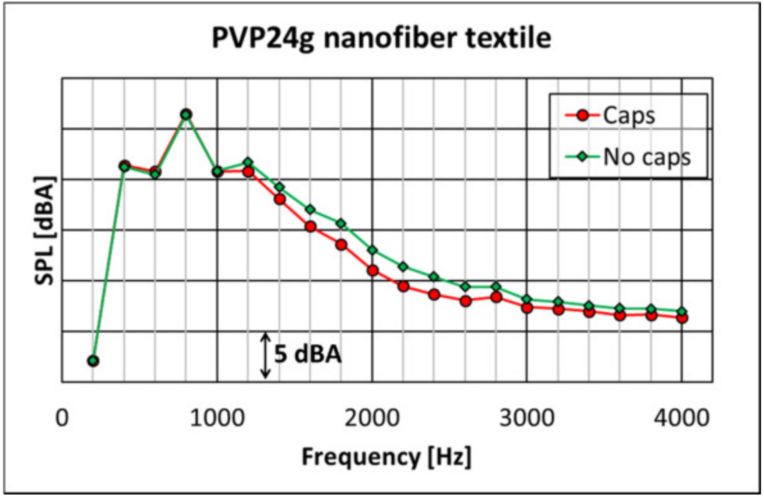
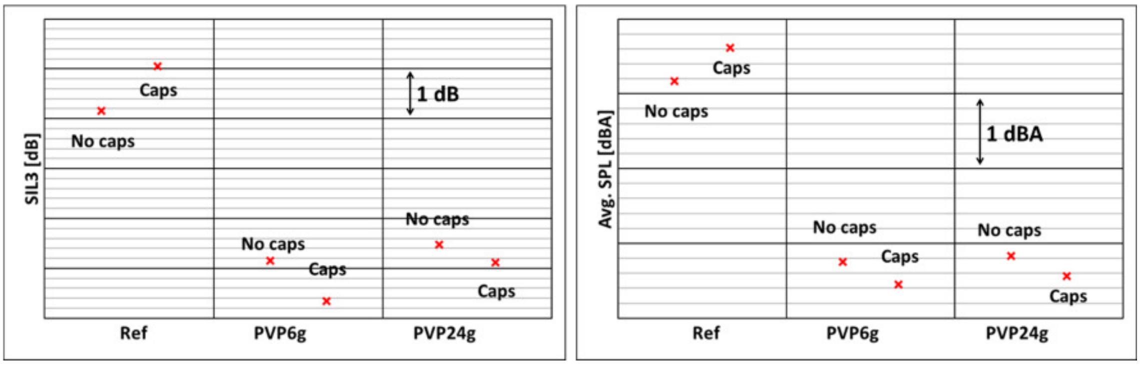


(c)

Figure 8: SPL [dBA] on the data recovery surfaces considering headrest with/without caps and surface impedance of: (a) reference textile, (b) PVP6g nanofiber textile, (c) PVP24g nanofiber textile.



(a) (b)

Figure 9: (a) SIL3 [dB] and (b) average SPL [dBA] for various headrest configurations.

4. CONCLUSIONS

The two technologies of headrest shape optimization and covering textiles, demonstrated to be effective in lowering the noise perceived by the passengers inside the cabin of an aircraft turboprop.

The adoption of a headrest with lateral caps seemed to play a positive effect for all the frequencies higher than 600 Hz. The adoption of high absorbing materials, such as the nanofibrous textiles, turned out to be effective in lowering the SPL perceived by passengers.

It is worth noting that the adoption of the PVP24g nanofibrous textile allowed an interesting noise reduction (-1 dBA) even at frequency as low as 200 Hz, thus foreseeing the possibility to adopt PNC even at such low frequencies. At higher frequencies, the adoption of a nanofibrous textile allowed a reduction in SPL up to nearly 3 dBA. For high frequency, the adoption of PVP6g seemed to be the most effective since the it demonstrated to be the most performant and also lightweight textile.

As a final conclusion, it is recommendable the simultaneous adoption of both approaches since their coupling enables higher noise reduction than achievable when the solutions are used as standalone.

5. ACKNOWLEDGEMENTS

The results have been mainly achieved in the framework of CASTLE – (CAbin Systems design Toward passenger welLbEing) Core Partnership of Clean Sky 2 Programme. CASTLE has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement n° CS2-AIR-GAM-2014-2015-01. The contents of this paper reflect only the author's views and the Clean Sky 2 Joint Undertaking and the European Commission are not liable for any use that may be made of the information contained therein. The SEA model has been derived from the CAD model of the Clean Sky 2 demonstrator, provided by LDOVEL.

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