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A Statistical Energy Analysis (SEA) model of a fuselage section for the prediction of the internal Sound Pressure Level (SPL) at cruise flight conditions

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A B S T R A C T

Comfort plays an increasingly important role in the interior design of airplanes. In general, comfort is defined as 'freedom from pain, well-being'; in scientific literature, indeed, it is defined as a pleasant state of physiological, psychological and physical harmony between a human being and the environment or a sense of subjective well-being. Cabin noise in passenger aircraft is one of the comfort parameter, which creates straightaway discomfort when exceeding personal thresholds. In general the cabin noise varies by the seat position and changes with flight condition. It is driven by several source types, which are transmitted through different transfer paths into the cabin. In the forward area the noise is mainly dominated by the turbulent boundary layer described by pressure vortexes traveling along the fuselage surface.

In this paper evaluation of the Sound Pressure level, for the medium-high frequency range, of an aircraft fuselage section at different stations and locations inside the cabin has been performed numerically by using Statistical Energy Analysis (SEA) method. Different configurations have been considered for the analysis: from the "naked" cabin (only primary structure) up to "fully furnished" (primary structure with interiors and noise control treatments) one. These results are essential to understand which are the main parameters affecting the noise insulation. Furthermore the Power Inputs evaluation has been determined to see the contribution of each considered aeronautic component on the acoustic insulation. Finally, the effect of a viscoelastic damping layer embedded in the glass window has been evaluated.

1. Introduction

Vibro-acoustic analysis is a necessary step for the virtual design of aerospace structures. In order to reduce the design costs and to maximize the acoustic performance of aerospace structures, a robust and mature prediction of interior noise levels is required. Interior noise is an essential topic to be considered in the design and operation of all aerospace flight vehicles. Noise is due to the combination of different sources such as: powerful propulsion systems, high-speed aerodynamic flow over vehicle surfaces and operation of on-board systems (air conditioners, pressurization system) [1,2]. High noise levels can be a negative aspect in the flight experience that can lead to problems such as passenger discomfort, interference with communication, crew fatigue, or malfunction of sensitive electronic equipment. They can produce temporary or permanent hearing loss, or cause other physiological symptoms, such as auditory pain, headaches, discomfort, strain in the vocal cords, or fatigue.

Noise is defined as undesirable sound and excessive noise can result in psychological effects, such as irritability, inability to concentrate, decrease in productivity, annoyance, errors in judgment, and distraction [3,4]. A noisy environment also can result in the inability to sleep or sleep well. Elevated noise levels can affect the ability to communicate, understand what is being said, hear what is going on in the environment, degrade crew performance and operations, and create habitability concerns. Superfluous noise emissions also can create the inability to hear alarms or other important auditory cues, such as the sound of an equipment malfunction [5]. In general, the noise level should be low enough to provide a feeling of comfort, avoiding in the noise spectrum excessive low-frequency "booming" or high-frequency "hissing".

The physics of noise transmission changes within a wide frequency regime, and its prediction can be evaluated by using various methods, according to the frequency range [6,7].

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In general, according to wavelength there are two basic approaches: deterministic and statistical.

In the low frequency range the behavior of a structure is deterministic and the basic tools applied for the analysis of vibration problems is finite element analysis (FEA) on the numerical side and experimental modal analysis (EMA) on the testing side [5]. Model validation of finite element models for the low frequency range is mainly based on the correlation of eigenvalues and eigenvectors from experiments and simulations. Modal analysis, based on finite element method, has a long history in application to dynamic problem on engineering structure system, but this kind of method can be only used to analyze the low modal order which can be clearly identified.

In the high frequency range, instead, the behavior of a structure is stochastic, which means that the statistics of the system have to be taken in consideration. The use of the energy-based approaches in the aeronautical industry field becomes more appropriate to describe the propagation of vibrational energy through the structure in the mid to high frequency range. Among these methods there is the Statistical Energy Analysis (SEA) [8–10], which can be used both as theoretical and experimental technique. It provides a framework for predicting the dynamic response and analyzing the vibro-acoustic transfer paths of "weakly coupled" and complex structural-acoustic systems. Engineering applications of the SEA in built-up structures normally involve the analysis of all relevant transmission paths and require a description of the power flow in a network of connected subsystems through the Coupling Loss Factor (CLF) [6,11].

SEA is widely used for prediction of interior noise in engineering transport applications (in automotive, railway and aerospace). In particular, the rigid requirements on noise level lead the aircraft companies to improve their design in terms of acoustic insulation and several studies can be found in literature [12,13].

In this paper, a fuselage section model of a turboprop aircraft has been modeled by using a SEA approach. The numerical model is provided by the use of the commercial software VA One, within the SEA module. An example of a SEA model using the software VA One can be seen in [14]. The aim is to establish a numerical model to evaluate the Sound Pressure Level in the aircraft fuselage section at different stations and location inside the cabin. Different configurations have been considered for the analysis: from the "naked" cabin up to "full furnished" with seats, stowage bins, etcetera. Moreover the Power Inputs evaluation has been determined to see the contribution of each considered aeronautic component on the acoustic insulation and a final investigation by using a different type of window with the addition of a transparent viscoelastic damping material has been performed. All the data herein presented (interiors layout, geometry, materials, etc.) have been used in accordance and under authorization of Leonardo SPA.

2. The basics of SEA theory

The SEA method is able to evaluate the vibrational response at high frequencies abd it is commonly used to predict interactions between reverberant sound enclosures and resonant structures [15].

The SEA model is commonly divided in a certain number of subsystems, which are linked by junctions that provide the exchange of power flow [6]. These subsystems can be the wave types in a component. This leads to a considerable flexibility in identifying the subsystems when creating a SEA model. There are some guidelines for creating the subsystems [16]:

- For any particular band, each subsystem should contain a minimum number of modes whose natural frequency falls within the band. The "minimum number" can be taken as three to seven; however there is no significant definition for this.
- The energy should be equipartitioned between the modes of a subsystem, which means that no single mode or a small group of modes will dominate the subsystems.
- The subsystems should be weakly coupled which means that if only one particular subsystem is subjected to excitation, the response of that subsystem will be significantly greater than that of any other subsystems.

Under random loads, the subsystems are subject to external power inputs. Power may be dissipated due to damping mechanisms. The power always flows from the subsystem which has a higher modal energy, or energy per mode, to the one having lower modal energy. The subsystems consist of similar resonant modes within a structure or acoustic space. For example, for a flat plate the bending waves, shear waves and longitudinal waves can be treated as separate subsystems. Moreover, the subsystems can also be the physical components of a complex system. These subsystems are coupled via junctions through whom the energy is transferred. The power flow between the subsystems is proportional to the differences of the modal energies of the coupled system and the energy is dissipated within a subsystem related through loss factor. According to the basic concepts of SEA, the procedures are formulated by making the following assumptions:

1. The excitation spectrum is broadband and the excitation forces are statistically independent. There are no pure tones in the input spectra.
2. There is no energy generation or dissipation in the couplings between the subsystems.
3. The damping loss factor is the same for each mode within a subsystem and frequency band.
4. Modes within a subsystem do not interact except to share equipartitioned energy.

The power always flows from the subsystem which has a higher modal energy to the one having lower modal energy trough dynamic equilibrium. These arguments are synthesized in the following equation:

$$P_{ij} = \omega(\eta_{ij} E_i - \eta_{ji} E_j) \tag{1}$$

where ω is the analysis band center frequency; η_{ij} and η_{ji} are the coupling loss factors when the power flows from subsystem i to subsystem j and from subsystem j to subsystem i, and E_i and E_j are the uncoupled total subsystem energies. SEA assumes that in narrow frequency bands, all modes have the same energy at steady-state. Here, an important reciprocity relationship for SEA must be introduced:

$$\eta_{ij} n_i = \eta_{ji} n_j \tag{2}$$

In this equation, n_i represents the modal density of the element in the interested frequency band. By using Eq. (1) and Eq. (2), the general SEA power flow equation can be represented as:

$$P_{ij} = \omega \eta_{ij} n_i \left(\frac{E_1}{n_1} - \frac{E_2}{n_2} \right) \tag{3}$$

The total energy in each element in a frequency band with a center frequency of ω can be found by the equation:

$$E_i = n_i e_i \tag{4}$$

where e_i represents the modal energy of the element. Moreover, the power dissipated within the system can be found by using the internal loss factor of the element, η_i, with the equation:

$$P_{i,diss} = \omega \eta_i E_i \tag{5}$$

By using Equation (3) and Equation (5), the power balance for subsystem i can be written as:

$$P_{i,in} = P_{i,diss} + P_{ij} \tag{6}$$

$$P_{i,in} = \omega \eta_i E_i + \omega \eta_{ij} n_i \left(\frac{E_1}{n_1} - \frac{E_2}{n_2} \right) \tag{7}$$

In most general form, for a complex system having more than two subsystems connected to each other, for example s subsystems, equation (7) can be written as:

$$P_{i,in} = \omega \eta_i E_i + \sum_{j=1}^{s} \omega \eta_{ij} n_i \left(\frac{E_i}{n_i} - \frac{E_j}{n_j} \right) \tag{8}$$

To implement SEA for a system that is comprised of N subsystems, the power balance equations are expressed using the following generalized matrix solution [8,9] to determine the energy vector from:

$$\{P_{in}\} = \omega [L] \{E\} \tag{9}$$

where ω is the central frequency of a frequency band, E is the energy vector and P_{in} is input power vectors, [L] is the loss factor matrix that includes the damping loss factors and coupling loss factors, whose elements are given by:

$$L_{ij} = \begin{cases} -\eta_{ij} & i \neq j \\ \sum_{k=1}^{N} \eta_{ik}, & i = j \end{cases} \tag{10}$$

Here, the damping loss factor and coupling loss factor are determined by the characteristics of the subsystems themselves. According to equation (10), if the system parameters (loss factors η_i, coupling loss factors η_{ij}, modal densities n_i, power inputs and the analysis center frequency) are known, the energy distribution of the subsystems can be found. In summary, the general procedure for SEA calculations is as follows:

1. Specify the frequency bands for the analysis;
2. define the subsystems;
3. calculate the subsystem properties, namely modal density, loss factor and the coupling loss factor;
4. determine the external power input to each subsystem;
5. formulate the power balance equation, which is the equation (8);
6. solve the equation to obtain the average energy in each subsystem;
7. convert average subsystem energies into desired response quantities.

3. SEA model of a fuselage section

A fuselage section has been modeled using the software VA One, through the SEA module. It is 7.2 m long and it refers to the first section of the fuselage (the closest to the engine).

A side view of the SEA fuselage model is shown in Fig. 1. It can be noted that the fuselage section has been divided in 6 subsections in order to distinguish the Sound Pressure Level (SPL) along the fuselage at 6 different stations, necessary to evaluate the noise level at various distances from the noise source. The subsection I is the farthest from the turboprop engine source: the VI the closest one and hence the most loaded, although in this study the tonal loads in the low frequency range are neglected.

A front view of the SEA fuselage model is shown in Fig. 2, where it can be noted the internal suddivision through the cavities.

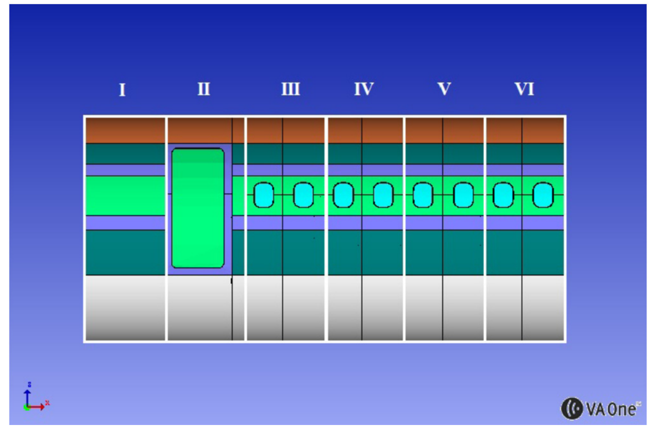


Fig. 1. Side view of the SEA model. Fuselage section partitioning.

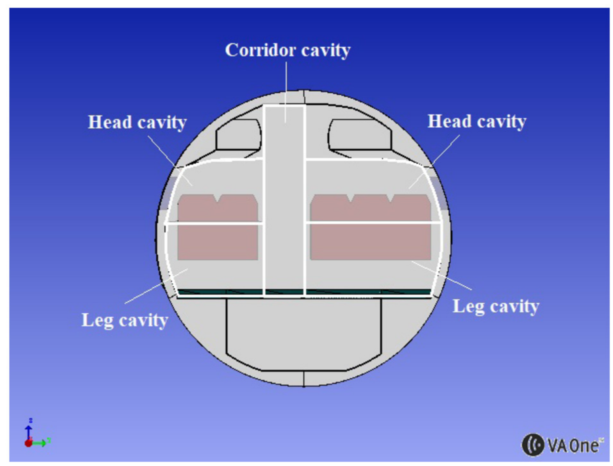


Fig. 2. Internal arrangement of the SEA acoustic cavities over a subsection.

A cavity is a SEA subsystem defined in VA One with the physical property of an acoustic fluid. A fundamental property associated to a cavity is the damping coefficient, that can be defined as: damping loss factor, absorption from noise control treatment or average absorption.

The internal arrangement of the acoustic cavities is shown in Fig. 2. It can be noticed that the internal pattern is divided in 3 main zones, which are named as follows:

- Head cavity
- Leg cavity
- Corridor cavity

This kind of division of the SEA acoustic cavities is useful to understand how the SPL is distributed over a subsection. In particular, the attention has been focused on the “Head cavity”, because the energy level measured in this cavity is correlated to the SPL perceived by the human ear.

The seating arrangement is shown in Fig. 3. It can be seen that there is a 3 + 2 seat layout, so it is not-symmetric. The seats have been modeled using a typical aeronautic seat foam, which, as the noise control treatments, provide an absorption of the vibrational energy inside the cabin, and hence the reduction of the noise level too, when they are installed aboard.

Finally the SEA model including the application of the external loads and the Semi Infinite Fluids (SIF) is reported in Fig. 4. The fuselage section has been represented with 582 SEA plates and 126 acoustic cavities and the input power has been derived from a turbulent boundary layer (TBL) model.

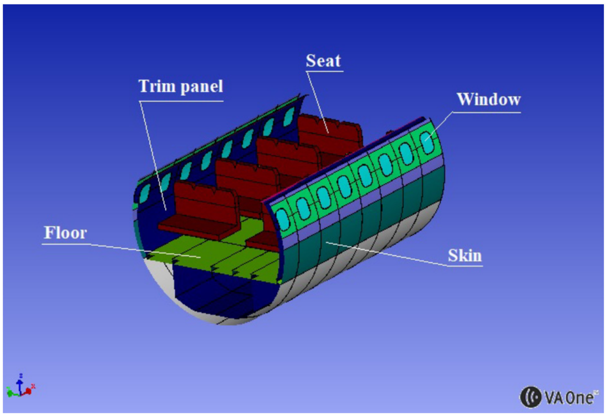


Fig. 3. Seating layout arrangement.

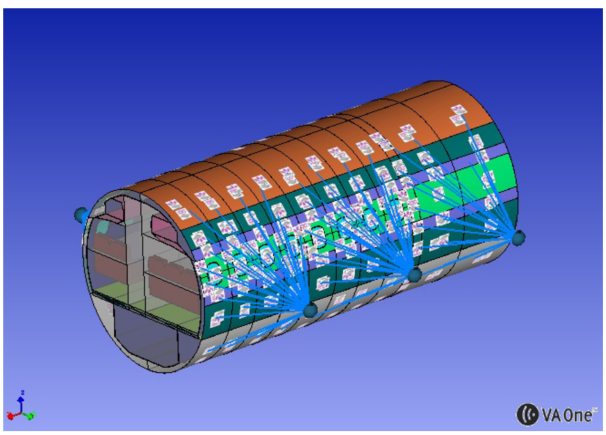


Fig. 4. SEA model of a fuselage section including the application of external loads and SIF.

The Turbulent Boundary Layer (TBL) has been calculated by the software [18], following two characteristics:

1. a band-limited RMS pressure spectrum, considering the Robertson semi-empirical model [19,20];
2. a narrowband Spatial Correlation Function between the pressure fluctuations at any two points on the loaded surface.

The parameters required for the TBL calculation are listed below:

- $U_0 =$ free stream flow velocity
- $X_0 =$ distance from the leading edge of the TBL to the center of the pressure load on the surface of the subsystem
- $\delta =$ Turbulent Boundary Layer Thickness (defined as the distance from the wall where the fluid velocity equals 99 percent of the free stream velocity)
- $c_x, c_y =$ the spatial correlation coefficients of decay in the along-flow and cross-flow directions
- $k_x, k_y =$ the projections onto the local axes of the convection wavenumber k_c

The root mean square spectrum due to TBL has a mean value of 105 dB.

Furthermore, the Semi Infinite Fluid (SIF) represents an unbounded exterior acoustic space. The acoustic waves radiated by a subsystem connected to a SIF are not reflected back on the subsystem.

Fig. 5. Typical sidewall treatment of a large passenger transport aircraft.

Table 1
Properties of the *glass wool* blanket.

Properties of the *glass wool* blanket	
Porosity	0.99
Tortuosity	1
Viscous characteristic lengths [m]	0.000192
Thermal characteristic lengths [m]	0.000384
Flow resistivity $\left[\mathrm{Ns/m^4}\right]$	9000
Density $\left[\mathrm{kg/m^3}\right]$	16

3.1. Materials

A fuselage section is a complex structure made of several different materials, both isotropic and orthotropic. In view to have a clear view of the material distribution a list of the materials used for each fuselage component is here reported and shown in Fig. 3:

- **Skin**: Composite panels made of carbon fiber reinforced epoxy resin having different lay-up and stacking sequence according to the component.
- **Trim panel**: Sandwich panels consisting of a thermoplastic foam core embedded between two skins made of fabric glass.
- **Floor**: Isotropic panel made of rigid foam covered by a carpet.
- **Seat**: Aluminum structure covered by a typical aeronautical seat foam.
- **Window**: A thick window layout composed of a tempered glass, airgap and plexiglass clamped between two aluminum frames.

Furthermore, over the structural materials, in order to reduce the internal noise, in such case a soundproofing material is added to the structure. A typical fuselage is composed of a skin, stiffeners and frames, an insulation layer and an interior wall. The absorption materials, such as the fabric and the soft foam, are usually used in the insulation layer to improve the sound insulation (Fig. 5). The main functions of this kind of materials are: i) to suppress acoustic resonances of the cavities that would otherwise strongly couple the two panels: ii) to decouple the trim sheet (interior wall) from the vibration field induced in the outside structural shell by various acoustic and mechanical sources.

In this work a 10 cm thick of glass wool blanket has been used by means of the application of Noise Control Treatment (NCT). The characteristic properties are reported in Table 1, while the absorption coefficient is reported in Fig. 6.

3.2. Fuselage section configurations

The interior noise is affecting mainly by the fuselage structure and the acoustic treatments in the cabin. A calculation procedure that can rigorously handle these elements and their interactions is not yet available. Therefore approximate methods are required, such as the bottom-up approach where the Sound Pressure Level is calculated step by step starting from the basic primary structure (*naked*) up to the fuselage including the interiors and the secondary structures (*fully furnished*).

The analyzed configurations are:

Configuration A: the fuselage section has been modeled considering only the primary structures, as can be seen in Fig. 7a.

Configuration B: the model includes the primary and secondary structures, but no interiors have been installed. As can be seen in Fig. 7b the internal arrangement of the SEA cavities is unchanged respect to conf. A. The difference is the presence of the air gap cavities between the skin panels and the internal panels.

Configuration C: the arrangement of the model is the same of the conf. B, but in this case the NCT has been added between the primary and secondary structures.

Configuration D is a result of the conf. B including the interiors (seats, stowage bins), as can be seen in Fig. 7c.

Configuration E is a result of the conf. D including the presence of NCT between the primary and secondary structures.

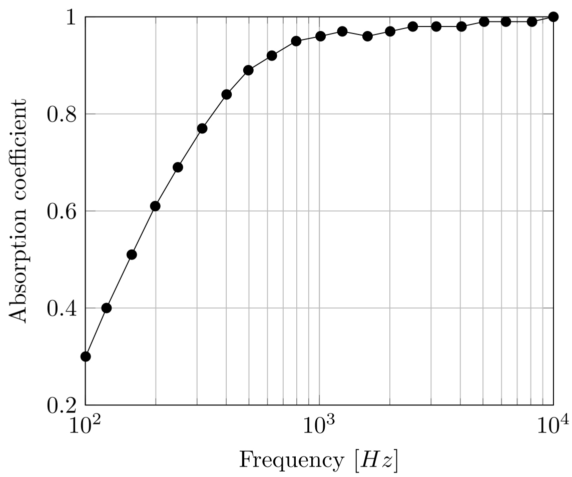


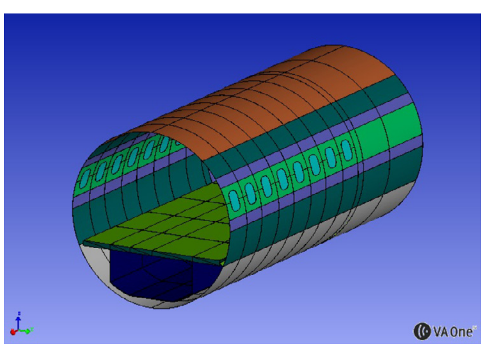
Fig. 6. Absorption coefficient of a 10 cm width glass wool layer.

4. Results

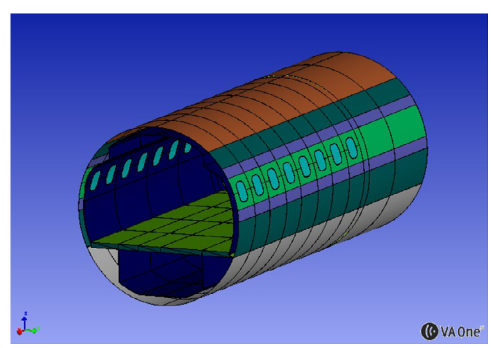
Numerical prediction of the interior noise level for the different configurations of the fuselage section has been performed at cruising flight (altitude=6000 m and flight speed=177.5 m/s). The values of kinematic viscosity, density and speed of sound at 6000 m of altitude have been given to the exterior fluid. These values have partially characterized the TBL and SIF parameters applied to each panel of the model. For the internal cavities, the parameters of the fluid correspond to those at sea level. In each section of the fuselage X_0 was given considering a value starting from 3 m in section I up to 10 m in the last one, section VI, as shown in Fig. 8.

Before to discuss the results it is useful to report some few notes on the acoustic parameters that have been defined to quantify the interior noise level. The Sound Pressure Level (SPL) is a logarithmic measure of the effective pressure of a sound relative to a reference value. SPL is measured in dB and is defined by:

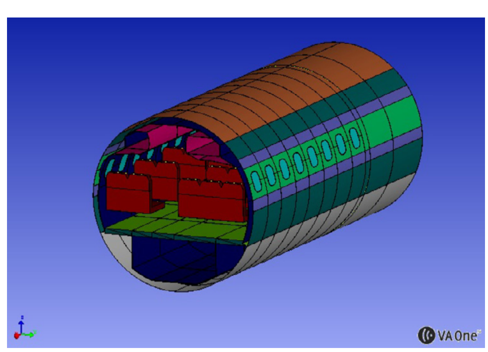
$$SPL = 20Log_{10}\left[\frac{p_{RMS}}{p_0}\right] \quad (11)$$



(a) SEA model of a fuselage section. Configuration A



(b) SEA model of a fuselage section. Configuration B



(c) SEA model of a fuselage section. Configuration D

Fig. 7. SEA model of a fuselage section. Different configurations analyzed.

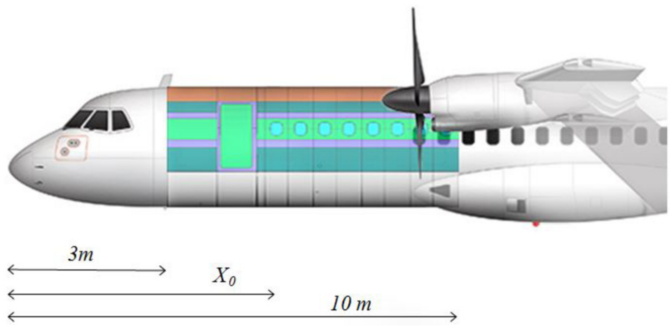


Fig. 8. Description of the parameter X_0 used for the TBL calculation along the fuselage section.

where p_{RMS} is the root mean square pressure in a certain frequency band with frequency bandwidth Δf and p_0 is the reference sound pressure equal to 20 μPa. The Overall Sound Pressure Level (OASPL, dB), adds most audible frequency components equally. The A-weighted sound level (dBA) is widely used to assess the human perception of sound. Humans are most sensitive to the frequency range 1000-10000 Hz, so it considers a lower weight for the components of sound at very-low and high-frequencies. It has been shown, using simulated cabin noise, that 50 percent of subjects reported feelings of annoyance when the A-weighted level exceeded about 82 dBA [17].

As it is well known, the accuracy of the SEA analysis increases with the raise of the Modal Overlap Factor (MOF). Generally, a MOF higher than 1 provides a good reliability of the results. This happens because, at low frequency, where there are few modes, SEA results are poor and exact results present a high sensitivity to the position of the excitation point. Increasing frequency, modal overlap factors and modes number increase; then SEA results are better and the sensitivity to the position of excitation decreases. The explanation is that increasing the damping smooths the frequency response functions of the systems, making them less sensitive to variations in structural details. There are empirical rules that say that the statistical variances are acceptably small if the modal overlap factors of the subsystems are greater than a certain value (1.0 is a commonly quoted number). The MOF associated with the SEA cavities of the model is higher than 1 starting from the frequency 1000 Hz. For this reason, the frequency range that has been adopted in the analysis is 1000-10000 Hz.

The first represented results are the distribution of the SPL over the interior cavities of the fuselage model for the different configurations. The SPL has been plotted in dBA to better represent the human ear perception of noise. Fig. 9 shows the SPL evaluated at 'Head Cavities' for some section and for all the 5 investigated configurations. The Figs. 9a, 9c, 9e refer to the cavities which correspond to the three-seat layout, while the Figs. 9b, 9d, 9f to the cavities which correspond to the two-seat layout. These results are related to the region of space occupied by passengers' ears.

As can be seen from the Fig. 9 the trend of the SPL curves is always the same for all the configurations and the analyzed cavities: the SPL decreases as the frequency increases. The parameters that mainly affect the SPL are: the Damping Loss Factor (DLF) of the materials and the absorption coefficients of the NCT and of the foam present on the seats.

The plot of all these curves is very important because they make in evidence the influence of the parameters on the SPL. In fact, while for the *configuration A* (only primary structure) the SPL variates between 93 dBA at 1000 Hz and 65 dBA at 10000 Hz; for the *configuration B*, i.e. primary structure plus the trim panels, the SPL variates from 89 dBA at 1000 Hz to 47 dBA at 10000 Hz, which is 18 dBA lower than the previous case.

For the *configuration C* it is possible to see the effect of the NCT on the sound insulation. In fact, the SPL curve in this case is constantly lower, about 7 dBA, than that of the *configuration B*. As consequence the OASPL too is lower.

From the SPL curves of the *configurations D* and *E* it is possible to see the effect on SPL due to the presence of the interiors inside the cabin. The SPL values related to the *configuration D* are much similar to the ones of the *configuration C*. This happens because the amount of absorbing material used for the seat layout provide a sound reduction comparable to the NCT ones.

The SPL curve of the *configuration D* is fundamental to understand the effect of the interiors on noise reduction. It is interesting to see that the SPL values of the *configuration E* is much lower than the other configurations and also the effect of the seat layout provide differences not negligible. The SPL curve associated to the cavities over a three-seat layout is 3 dBA lower than the SPL values related to the cavities over the two-seat layout.

In order to better represent the next results, an enumeration of the SEA cavities has been specified as shown in Fig. 10, where it has been considered all the "head cavities" and "aisle cavities".

In Fig. 11 the OASPL (dBA) for each cavity and for each configuration is shown. As it was expected, the worst configuration is the *configuration A*, since the OASPL is characterized by a constant trend with a value of 98 dBA for almost all the cavities considered. By adding first the secondary structures *configuration B* and then the NCT *configuration C* to the fuselage section the OASPL reduces respectively of about 6 dBA and 10 dBA compared to *configuration A*.

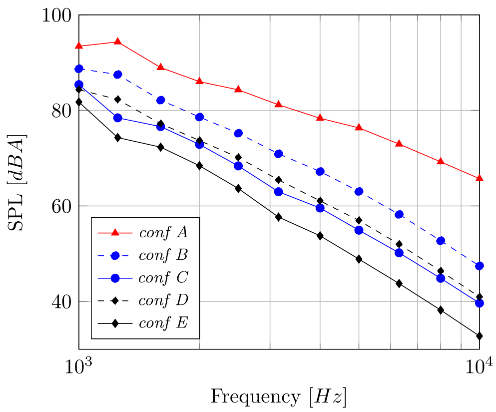
From this graph it is clear that the OASPL values of the first three configurations described is rather constant for all the cavities analyzed. This happens because the absence of the seat layout, which are characterized by damping material, provide a noise reduction inside the SEA cabin cavities.

Looking at the OASPL results of the *configuration D*, it is possible to observe the positive effect on the noise level due to the presence of interiors. In this case the average OASPL is nearly 86 dBA, about 6 dBA lower than the analogous case without the interiors and without the NCT, or rather, the *configuration B*. Furthermore, the OASPL is not constant over the fuselage; in fact it can be noted that it assumes different values according if it has been evaluated in the three-seat layout zone or the two-seat layout one. In the cavities defined over the three-seat layout, the result is even 3 dBA lower than the results observed in the cavities with a two-seat layout. This make in evidence how the presence of materials having good acoustic properties, such as the foam material of the seat, influences the SPL.

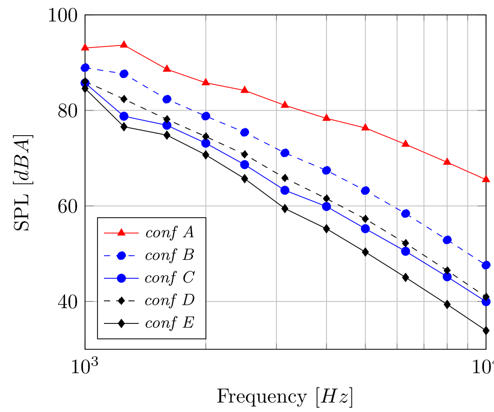
Among all the investigated configurations the "fully furnished" one (*configuration E*) shows the minor OASPL, with an average value of 82 dBA. In this case too, it is notable the difference in OASPL over the two-seat layouts. As consequence of these results, it is possible to assert that the addition of soundproofing material is fundamental for the reduction of the internal noise inside the fuselage cabin. In effect, in order to keep the same OASPL over the different seat-layouts, a solution could be increasing the thickness of the glass wool layer along the two-seat layout side, providing a higher damping of the vibrational energy inside the cabin, paying attention to weight gain.

Fig. 12 reports the contour plot of the OASPL of *configuration E*. The colored representation helps the reader to note the difference in noise level for different passenger positions and along the fuselage. The information of main interest is the difference between the OASPL over the two sides of the fuselage. The assessed OASPL variates from 78 dBA to 85 dBA when moving from the two-seat layout to the three-seat layout respectively.

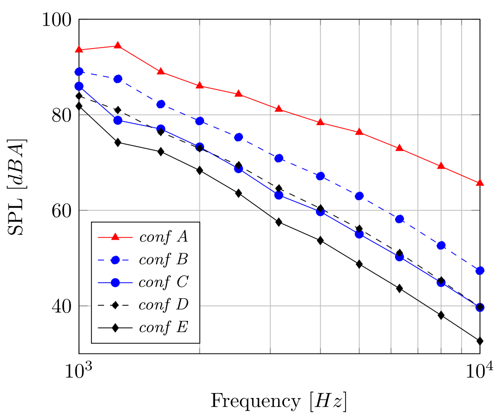
In SEA the investigated system is divided into a set of couple subsystems, each of one represents a group of modes with similar



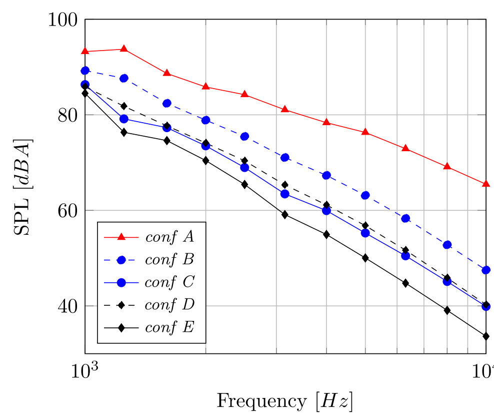
(a) Head cavity: Sec. III - three-seat layout side



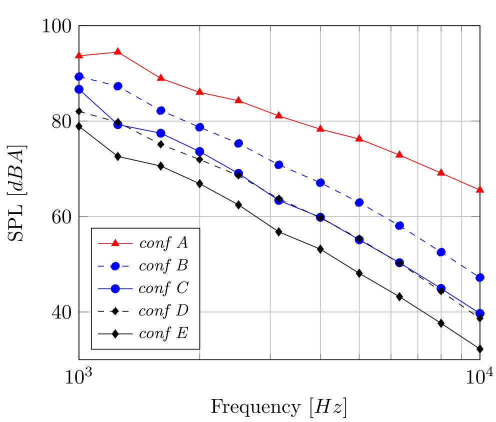
(b) Head cavity: Sec. III - two-seat layout side



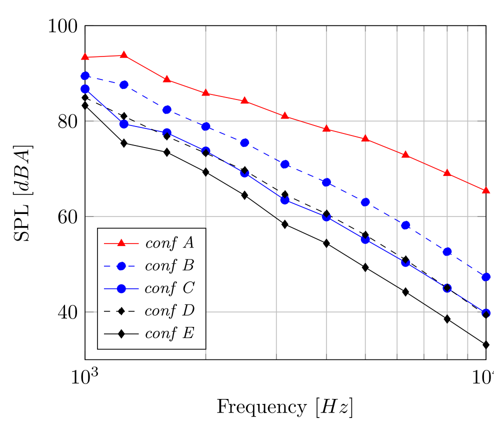
(c) Head cavity: Sec. IV - three-seat layout side



(d) Head cavity: Sec. IV - two-seat layout side



(e) Head cavity: Sec. VI - three-seat layout side



(f) Head cavity: Sec. VI - two-seat layout side

Fig. 9. Comparison of the SPL evaluated at Head cavities, in the frequency range 1000-10000 Hz, of the analyzed configurations.

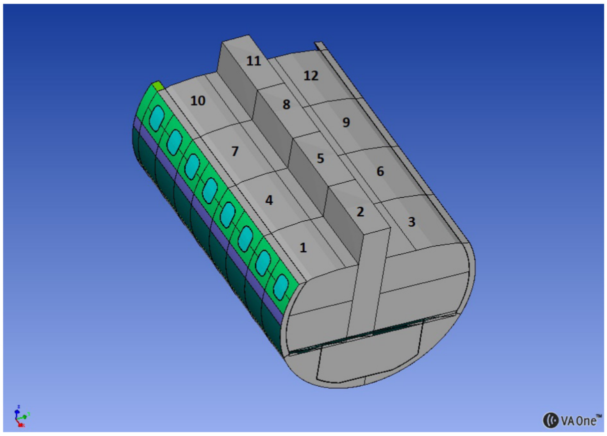


Fig. 10. Internal enumeration of the SEA cavities along the fuselage section.

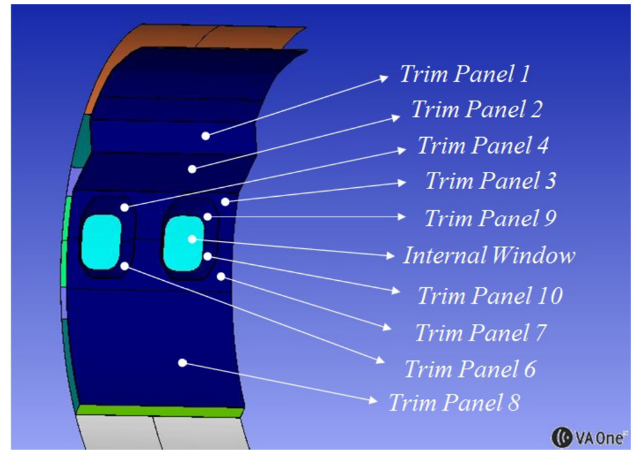


Fig. 13. Internal nomenclature of the SEA panels.

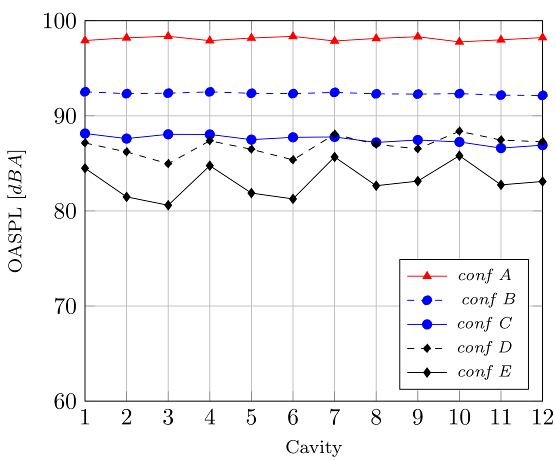


Fig. 11. OASPL over the cavities present in the fuselage section. Comparison between the configurations analyzed.

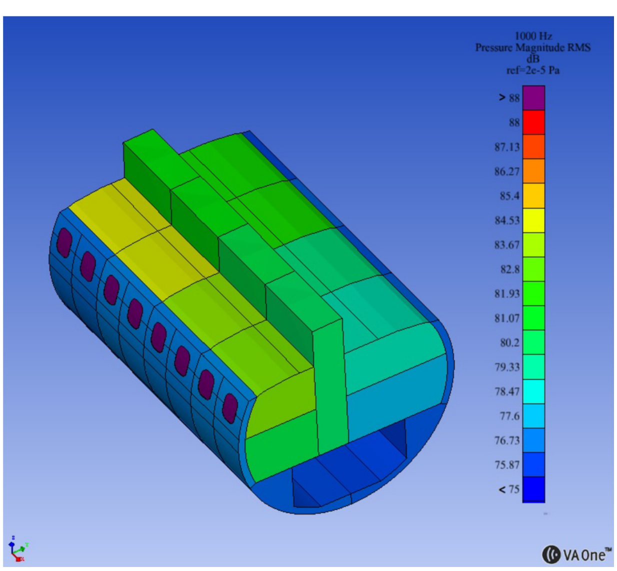


Fig. 12. OASPL (dBA) inside the aircraft cabin of the *Configuration E*. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

characteristics. The energy source contribution of each subsystem to the inner sound field is accessed through their coupling loss factors. For each subsystem the sound power level transmitted to the acoustic cavity facing with it is assessed. The Power Input make in evidence the single subsystem contribution to the Sound Pressure Level. Since the number of subsystems of all the fuselage is high (for instance Fig. 13), in order to make the representation of the results more comprehensible the Power Inputs refers to the Head Cavity of the section III over the two-seat layout of *configuration E*.

The results are shown in Fig. 14, considering the configurations B, C, D and E.

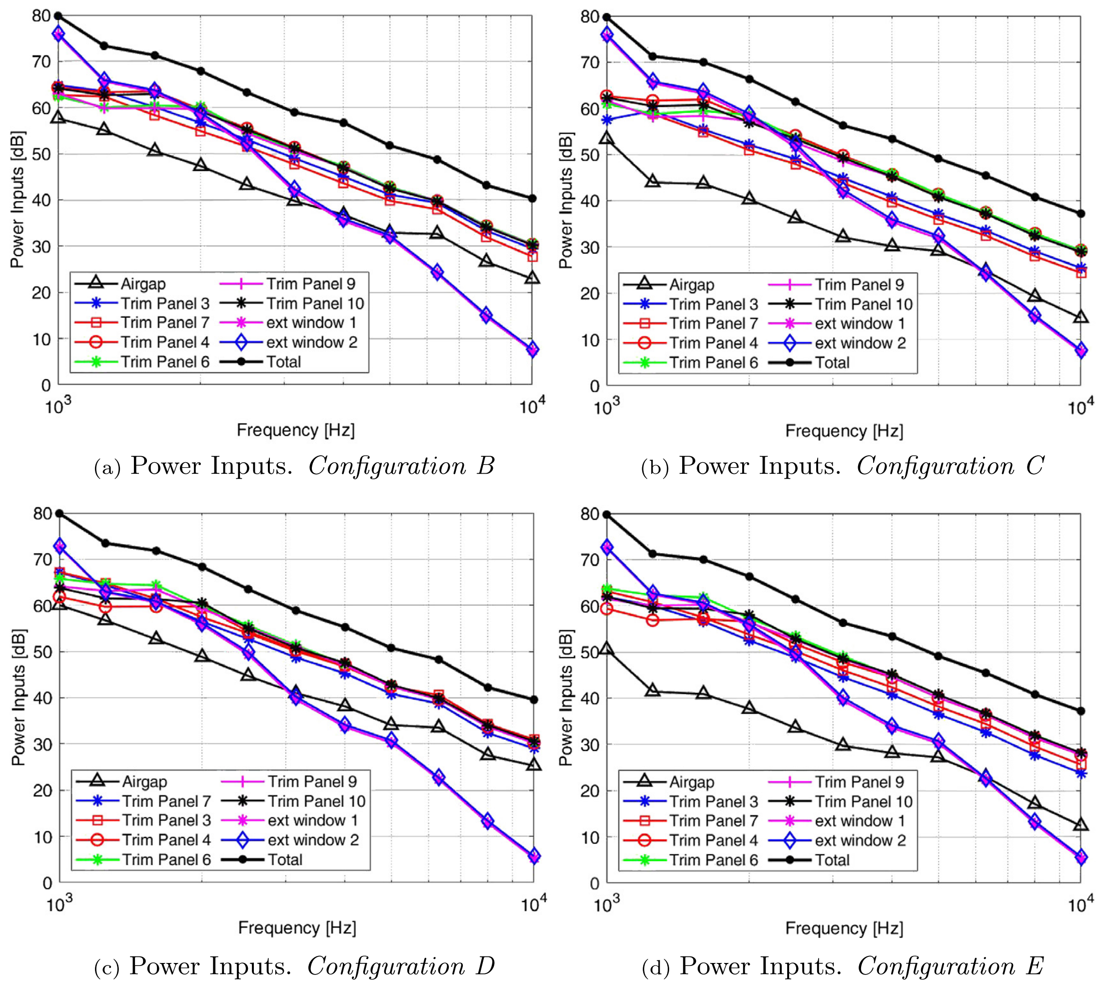
It is possible to see that the main sources for this cavity that contribute to a high SPL are those closer to the windows. For each considered configuration, the highest source in the frequency range 1000-2000 Hz is provided by the external windows, while at highest frequencies the SEA subsystems that provide the highest energy source are those around the windows.

Furthermore, it can be seen that starting from 2000 Hz, the Power Inputs related to the configurations without the presence of NCT, are quite higher than those of the configurations with the NCT. This happens because the NCT provide a damping of the vibrations that come from the SEA subsystems, that are in turn excited by the external loads.

The Power Inputs evaluation is fundamental to understand which are the subsystems that involve the highest source of energy inside the cabin. Thanks to this, a correction on the subsystems' parameters, such as thickness, materials and geometry can be considered to improve the sound insulation properties. In this case a good solution to reduce the energy transmitted inside the cabin could be increasing the thickness of the panels around the windows, or maybe, changing materials which they are made of.

From the analysis of the obtained results a new analysis has been decided to be performed by considering a different window layout, having the same mass of the previously one, in order to reduce the structure-borne and the air-borne noise transmitted into the interior. For the new window layout, the 3 mm thick layer of tempered glass has been substituted with two layers of tempered glass (1.7 mm and 1 mm) with transparent viscoelastic damping material embedded between the layers, which has a thickness of 0.6 mm, as shown in Fig. 15. The used viscoelastic damping material is the Solutia Saflex, which has a density of 1068 kg/m^3. Poisson ratio pairs to 0.499, while the shear modulus and the damping coefficient varies with frequency.

In Fig. 16 the comparison of the SPL in the aircraft interior between the *Configuration E* and the *Configuration E + Viscoelastic interlayer* in the frequency range 1000-10000 Hz is shown. In this case it has been considered only the Head Cavity of the section III



(a) Power Inputs. *Configuration B*

(b) Power Inputs. *Configuration C*

(c) Power Inputs. *Configuration D*

(d) Power Inputs. *Configuration E*

Fig. 14. Power Inputs referred to the Head Cavity in sec. III over the two-seat layout. Frequency range: 1000-10000 Hz. Different configurations analyzed.

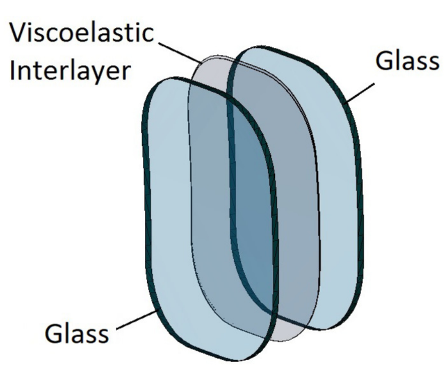


Fig. 15. Viscoelastic interlayer sandwiched between two tempered glass layers.

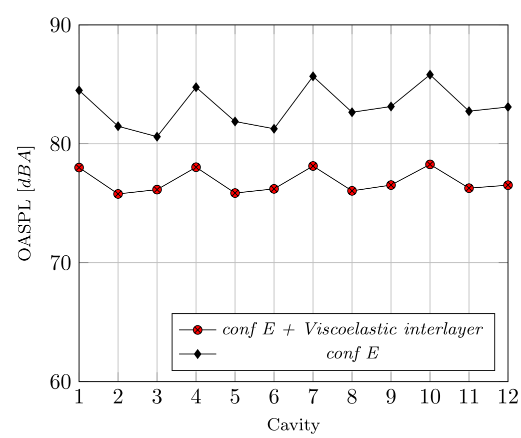


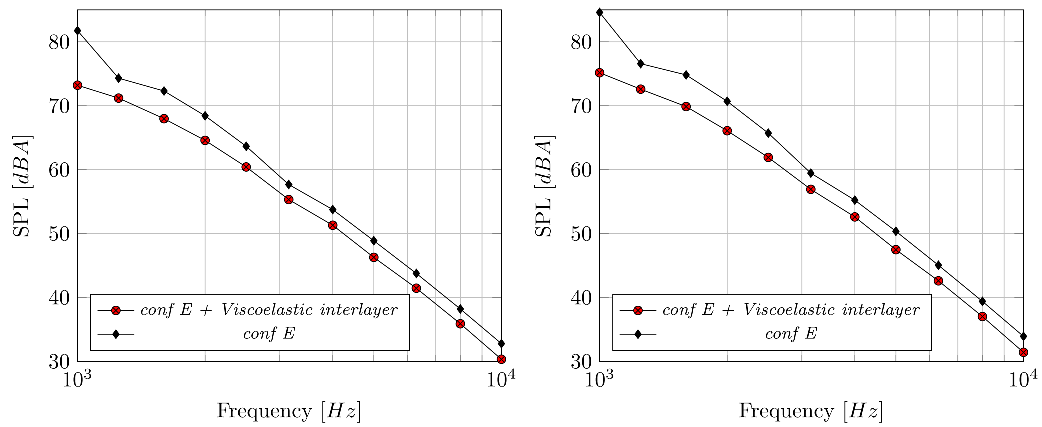
Fig. 16. OASPL over the cavities present in the fuselage section. Comparison between the *Configuration E* and the *Configuration E* + *Viscoelastic interlayer*.

because it appears to be the most critical in terms of internal SPL. It is possible to see that the improvement provided by the presence of the viscoelastic interlayer are quite evident at 1000 Hz, where the SPL is 4 dBA lower than the *Configuration E* case, while starting from 1500 Hz the improvement is constantly equal to 1 dBA.

The comparison of the OASPL between the *Configuration E* and the *Configuration E* + *Viscoelastic interlayer*, along the cavity numbered (as in Fig. 10) is shown in Fig. 17. It is possible to notice that the presence of the Saflex interlayer ensure an OASPL 6 dBA lower than the one evaluated for the *Configuration E*, in both the cavities over the two-seat and three-seat layout.

5. Conclusion

This paper presents an evaluation of the Sound Pressure Level (SPL) of an aircraft cabin by means of Statistical Energy Analysis method. In view to highlight the parameters affecting the SPL, a sensitivity analysis has been performed. In particular, five configurations have been analyzed, starting from the evaluation on the primary structure to the evaluation of the complete fuselage section, including trim panels, interiors and passive noise control



(a) Head cavity: Sec. III - three-seat layout side

(b) Head cavity: Sec. III - two-seat layout side

Fig. 17. SPL over the Head cavities. Comparison between the *Configuration E* and the *Configuration E + Viscoelastic interlayer*. Range of frequency 1000-10000 Hz.

materials. Analysis have been performed in the frequency range 1000-10000 Hz considering as input the Turbulent Boundary Layer load. For all the investigated configurations, the trend of the SPL curves is always the same: it decreases at increasing of the frequencies. The difference in SPL value depends on the configurations and hence on the parameters taken into account. For example the difference of OASPL between the model of the fuselage section considering the only primary structure (*configuration A*) and the model of fuselage section considering interiors and NCT too (*configuration E*) is considerable, even of 16 dBA. Results have shown that soundproofing materials used for the passive control (glass wool blanket) and for the seat configuration (typical aeronautical seat foam) give a great contribution to the noise reduction. The application of a 10 cm thick layer of glass wool is able to reduce the SPL of about 10 dBA. The definition of interiors inside the cabin (seats, storage bins) produce a strong noise absorption. The difference on SPL are strongly appreciable even moving from a two-seat layout to a three-seat layout.

Finally, a new window layout, consisting of a viscoelastic damping layer embedded between two tempered glass layers, has been defined. This new layout has provided a significant reduction of the internal SPL, that is about 6 dBA for the cavities close to the windows. These results have shown that the use of viscoelastic layers for a new window layout can be a valid alternative to the conventional windows. Once again and even using a simplified model, a noise control plan is strongly recommended; it should be updated throughout the design, the manufacturing stages, and all flight phases of the vehicle. This noise control plan, in combination with monitoring and oversight of the design, development and verification efforts, is essential to achieve full compliance with the defined acoustic requirements.

Conflict of interest statement

The authors declare that there is no conflict of interest regarding the publication of this article.

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The studies performed on the new window layout, consisting of a viscoelastic damping layer between two tempered glass layers, are outside the activities of the project.

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