Chapter 12
Industrial Applications IV

Acoustic Package Optimization Methods in the Aeronautic Industry

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Abstract This chapter presents an overview of the challenges faced by the aeronautic industry on the search for a more efficient and comfortable cabin. In order to do that, the main noise sources are presented and characterized, together with a typical noise control treatment solution. Later, deeper focus on the porous materials use is described, presenting the difficulties for the characterization of such materials and consequently uncertainties on the project requirement's definition. Finally, some of the promising new studies on porous materials are discussed and their impact is evaluated in a case study.

12.1 Introduction

Air transportation became very popular during the last decades, being an affordable alternative for fast travel worldwide. With the popularization, new costumers' expectations arise and the decision on buying a flight ticket takes into account not only price but also the experience delivered. The importance of this experience increases on the business jet market where the expectations on the overall flight quality are higher.

One of the main topics related to the user experience is cabin comfort, in which noise and vibrations are two of the main factors that add to comfort perception [1, 2]. Quehl [2] showed that three of the top five attributes that compromise comfort during flight are related to noise and vibration. The proper estimation of cabin noise and

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the design of the Noise Control Treatment (NCT) present big challenges due to the aircraft complexity, with its various noise sources that act on a broadband spectrum. The knowledge of the factors that act on cabin noise was significantly improved over the past decades [3] and the results of this progress can be seen on better acoustic comfort, mainly on business aircraft, and on the increase of the NCT efficiency, that allowed reducing the overall treatment weight keeping noise levels low.

Despite the technology evolution, the demand for higher efficiency on noise control continues and improvements on current solutions are reaching their limit on current form, therefore the development of innovative solutions is required. One field that presents strong innovation potential is the design of porous materials and a lot of efforts are seen on the topic in the past years. The main difficulties developing and applying these new solutions are due to tight weight and space restrictions, and also to the severe aeronautic certification requirements.

This document aims at presenting an overview of the challenges faced by the aeronautic industry on the search for a more efficient and comfortable cabin. In order to do that, the main noise sources are presented and characterized, together with a typical NCT solution. Later, deeper focus on the porous materials use is described, presenting the difficulties for the characterization of such materials and consequently uncertainties on the project requirement's definition. Finally, some of the promising new studies on porous materials are discussed and their impact is evaluated in a case study.

12.2 Description of Noise Sources

Although variations will happen due to constructive characteristics of each aircraft, typical cabin noise sources for a jet engine aircraft can be divided in noise coming from the Turbulent Boundary Layer (TBL), from the engine and from onboard systems (Fig. 12.1). TBL noise is the main responsible source for the mid-frequency noise, the engine for low and mid frequency and the systems will contribute mostly for higher frequencies.

12.2.1 Engine Sources

The engine is responsible for distinct noise sources, with different generation and transmission characteristics. Firstly, unbalance in the low and high pressure shafts (called N1 and N2 respectively), generates vibrations that are transmitted through the engine fixture structure into the aircraft cabin interior. The unbalance energy is converted into noise through the interior liners, floor and monument's (galleys, lavatories, closets, bar units, refreshment centers, etc.) radiation. This type of source has a low frequency spectral content and it is tonal, making this a point of attention due to the human sensitivity for this type of excitation.

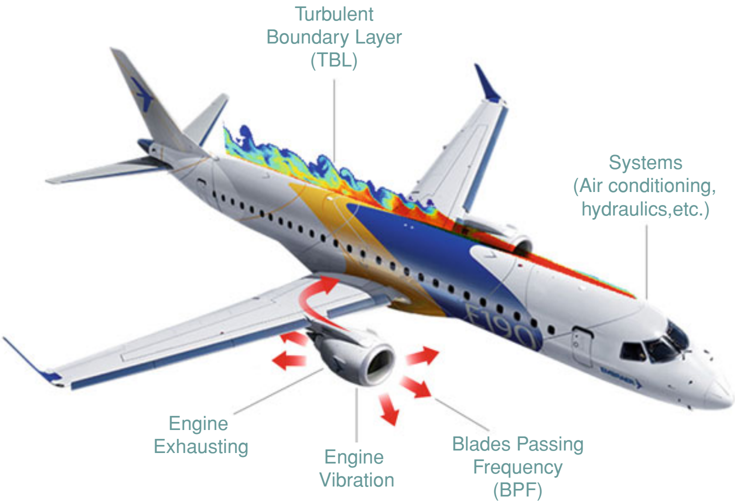


Fig. 12.1 Typical jet engine aircraft noise sources

Another noise source originated in the engine is the fan's Blades Passing Frequency (BPF). The excitation is also tonal, however the spectral content is much higher because it is the N1 rotational speed multiplied by the number of fan blades (usually some dozens of blades), and its higher harmonics.

Finally, another important engine noise source is caused by the exhaust gases turbulence. Unlike the aforementioned sources, this excitation has a broadband frequency spectrum, making the acoustic treatment strategy different from other engine sources. This kind of source may be relevant in wing mounted engines, impacting cabin zones located in the after portion of exhaust area.

12.2.2 Turbulent Boundary Layer (TBL)

The aerodynamic noise generated by the fuselage outboard pressure fluctuations due to the Turbulent Boundary Layer (TBL) is the main responsible for the cabin noise levels in the mid-frequencies, and for many cases, it is the main contributor for the overall noise level in the cabin.

In the TBL, there is a macroscopic movement of mass inside the layers of the boundary layer, thus generating an exchange of mass, momentum and energy. This pressure fluctuation travelling along the fuselage, dynamically excites the structure. There is part of energy directly radiated through the fuselage skin, and other part transmitted through the connection structures up to the interior parts, converting the vibratory energy into noise. Due to its nature, the TBL has got a broadband frequency content. The noise levels generated by the pressure fluctuation on the fuselage by

Fig. 12.2 Pressure level for different Flight Levels (FL). Mach = 0.8

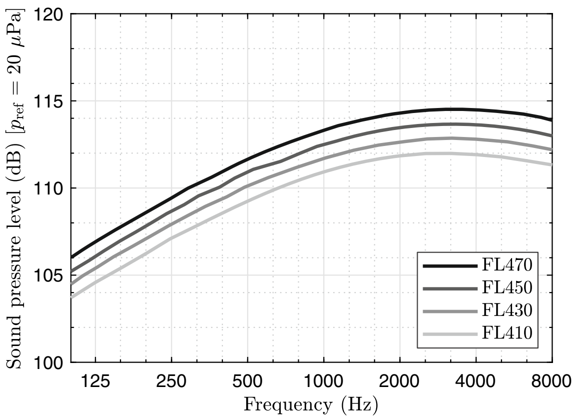
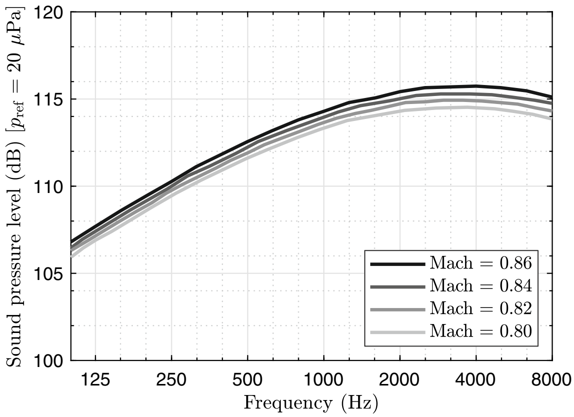


Fig. 12.3 Pressure level for different velocities. FL = 410



the TBL are directly associated with the aircraft flight altitude (Fig. 12.2), velocity (Fig. 12.3) and the distance from leading edge, i.e. TBL origin (Fig. 12.4).

The pressure estimation presented in results from Figs. 12.2, 12.3 to 12.4 were calculated [4] and will vary depending on other factors not listed here. But the sensitivity to velocity, altitude and distance will be similar.

12.2.3 Systems

Aircraft systems can generate several noise sources that may affect mainly the cabin noise perception (sound quality). The system's noise can be broadband, as those associated with the airflow inside the air-conditioning ducts, or tonal, as the noise generated by hydraulic pumps and cooling fans.

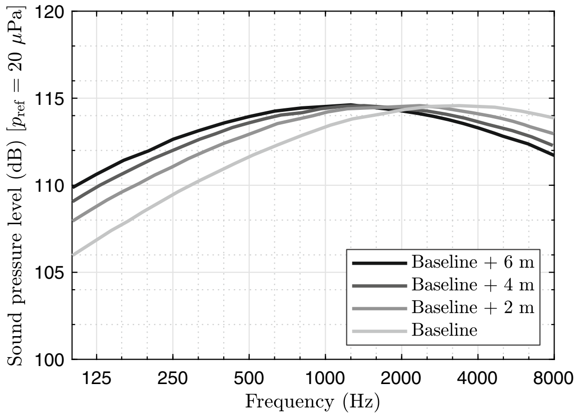


Fig. 12.4 Pressure level varying distance from TBL formation Mach = 0.8, FL = 410

Usually, the noise level generated by those systems does not impact the overall cabin noise level; however, the sound quality is affected if the proper countermeasure is not adopted. Furthermore, increasing the acoustic treatment performance for engine and TBL control, the systems noise tends to become more prominent, turning into the critical path for a more comfortable cabin.

12.3 The Use of Porous Materials

The choice of the vibroacoustic treatment strategy depends of the type of noise source, vibroacoustic energy path and the spectrum content. For instance, vibration caused by the engine N1 and N2 unbalance are typically attenuated using vibration isolators that act preventing the energy to be transmitted through the fuselage. For systems, the vibroacoustic control can be addressed in a variety of different strategies, depending on the system's specific characteristics. One of these strategies may be to act directly on the noise source, another may be isolating or attenuating the main energy path or, if those approaches are not feasible, the strategy can be the reallocation of the system far from the cabin.

The materials used to attenuate the energy that enters through the fuselage up to the interior liners is called Thermo-Acoustic Insulation System (TAIS). This set of materials actuates mainly in mid to high frequency and its typical components are presented in Fig. 12.5.

Viscoelastic material is applied in the fuselage skin in order to impose damping into the structure, reducing the skin vibration originated from the external sources. The Damping Loss Factor (DLF) is the key parameter for this material. Additionally, vibration isolators are employed to decouple the attachment between the primary structure (fuselage) and the interior liners, thus minimizing the structure-borne path. In order to attenuate airborne energy, porous materials are used, like fibers and foams.

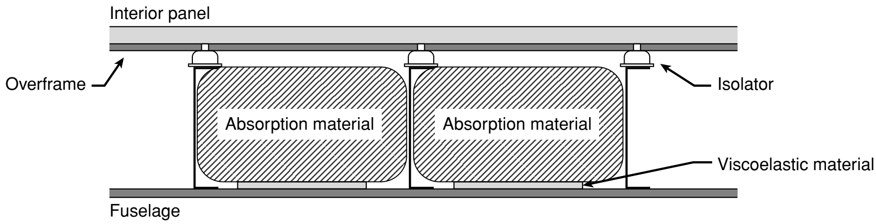
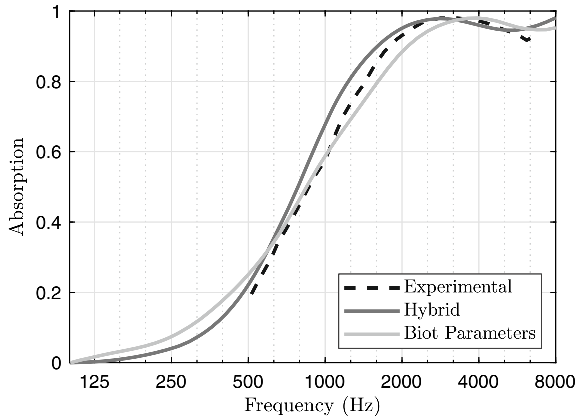


Fig. 12.5 Typical Thermo-Acoustic Insulation System (TAIS) configuration

Fig. 12.6 Absorption estimation of a fiberglass sample using different methods



Those materials are lightweight with a high acoustic absorption capability in mid to high frequency.

The attenuation in low frequency range is limited due to the material thickness, and it is directly related to the distance available between the fuselage and the interior liners. Acoustic absorption coefficient is the key parameter. Finally an overframe (barrier) is used to avoid airborne noise propagation. Area density is the key parameter in this case.

In order to minimize the TAIS thickness and weight, a proper characterization of each material is mandatory. In this context, the use of porous materials presents a big challenge since those materials are well known for their inherent uncertainties and experimental characterization results dispersion [5].

Initially, the porous materials must be characterized looking for its acoustic absorptive properties. This is traditionally made using plane waves excitation on an impedance tube [6] but can also be made by characterizing the material's Biot parameters [7, 8]. Alternatively hybrid methods can be used when initial experimental data is used to estimate Biot parameters through algorithms. All these methodologies present many advantages and disadvantages, and the results can vary significantly among them, as it can be seen in Fig. 12.6, where the acoustic absorption of a fiberglass sample is estimated using all three methodologies: Impedance tube measurement; Biot parameters measurement; hybrid methodology.

Differences like seen in Fig. 12.6 can lead up to 0.5 dB variations on the cabin noise estimation, which seems not much when looking isolated, but as the complexity of the analysis increases, these uncertainties propagate and sum with other uncertainties sources resulting in low precision models. A simplified development workflow for the noise control treatment starts with the material characterization, followed by a local treatment design and finishing with a full cabin analysis. The degree of uncertainty of the results increases when progressing on this workflow since the integration become more complex.

Additionally to the uncertainties from the different available methodologies, experimental tests to obtain acoustic parameters from porous materials also present high dispersion, as it can be seen at the study presented in [5]. In this study acoustic properties of three different porous materials were measured by several laboratories and the results were significantly different among them.

After material characterization the noise control treatment composition must be evaluated, i.e. the integration of the noise control solutions with the fuselage and the interior panel. In this way, the Transmission Loss (TL) of the NCT package can be estimated and the acoustic requirements can be tuned. This composition analysis can be performed analytically, experimentally and numerically, the later using deterministic, statistical or hybrid models.

Given the low computational costs and the theory constrains, Statistical Energy Analysis (SEA) models are commonly used for mid to high frequency analysis of the treatment when applied in regions with large dimensions. Deterministic and hybrid models are applied in low frequencies or local analysis, when specific characteristics of certain treatment regions must be evaluated, like geometry modifications or leaks.

For the experimental tests, the main challenge is to obtain good repeatability for the TL measurements. When performed in a high quality laboratory, at similar atmosphere conditions and by the same operator, the results tend to have low variation but if any of these parameters vary, the comparison among tests become challenging and conclusions inaccurate.

12.4 Aeronautic Requirements

Additionally to technical challenges of the TAIS design process, aeronautic certification requirements and industry regulation significantly limit the materials that can be used in the treatment, making optimization even more challenging.

One of the most restrictive requirements is related to flammability. The materials are submitted to tight fire self-extinguish, flame propagation, radiated panel burn and, in some cases, flame penetration tests (FAR/EASA 25.853 and 25.856). Another requirement that porous materials shall comply is the humidity retention, that according to norm ASTM C1511 [9], a maximum 20 g of water can be absorbed for a 10” × 10” × 4” sample of the porous material after 15 min submerged.

A common strategy to help the porous materials to comply with the flammability and humidity requirements is using specific chemical treatments, such as flame retardants or inhibitors which usually deteriorate acoustic performance. However, additionally to the previously mentioned requirements, regulations like the European REACH (Registration, Evaluation, Authorization and restriction of CHemicals) restricts the use of various chemical components, even if it is only used during an intermediate step of the fabrication process. Therefore, both the materials that are part of the TAIS and chemical treatments that those may be submitted are restricted.

12.5 New Developments

With the challenges presented in previous sections, the search for new developments that could reduce technological restrictions of the aeronautic industry is fundamental. Porous materials have been studied and developments have been made aiming the acoustic performance improvement, mainly at low frequencies where those materials perform poorly.

An easy way to increase the acoustic absorption of porous materials at low frequencies is increasing the material thickness, like presented in Fig. 12.7, where the plane wave absorption of a fiber is numerically evaluated for 1 and 3 inches.

Unfortunately, increasing the material thickness is usually not possible due to space limitation between the fuselage and interior panel, therefore innovative solutions have been studied to increase the absorptions at low frequencies avoiding thickness increase. Some studies focus on optimizing the treatment layers so that the impedance mismatch result in high absorption at desired frequencies. One example can be seen on [10], where the author presented some variations at the layer distribution of different porous materials, aiming for higher absorption values at lower frequencies.

An evolution of that concept is the porous materials microstructure design through porosity optimization presented by [11] that showed significant gains at the acoustic

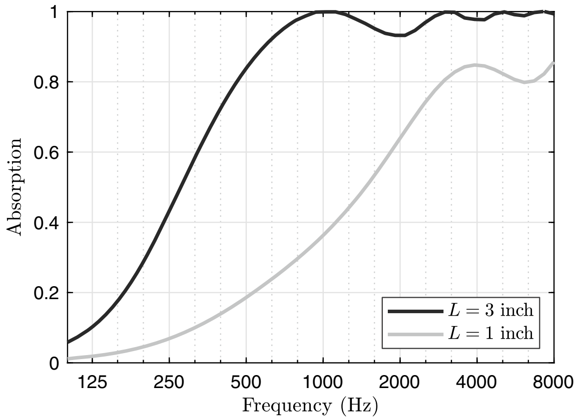


Fig. 12.7 Variation of the absorption with the porous material thickness

absorption characteristics by controlling the porous size of a foam sample. Another common research topic is the use of inclusions at porous materials in order to induce Bragg's scattering effect at the sample. These inclusions can significantly affect the energy attenuation as it can be seen in [12].

A straightforward expansion of the inclusions concept is the use of resonators inside the porous materials. This concept received attention for some time [13] and a recent example is presented in [14] where the author develop a study containing analytical, numerical and experimental analysis for resonators embedded in a porous material. The author concluded that significant TL gains may be expected at the resonator tuning frequency.

Recently the acoustic metamaterials concept have been explored [15] in which internal resonances are induced at the material in order to manipulate larger wavelengths than the expected for the base material, allowing elastic and acoustic energy attenuation at low frequencies. This concept has been expanded offering several different configurations such as membranes containing resonators [16] opening many possibilities to improve the aircraft acoustic treatment and performance.

12.6 Case Study

This section presents a typical scenario for an aircraft application. A simplified setup is presented in Fig. 12.8. The materials considered for this study are a 1.2 mm thick aluminium fuselage section, a 76.2 mm Fiberglass material with density (ρ) equal 8 kg/m^3, flow resistivity (σ) of 4000 N·s/m^4, porosity (ϕ) of 0.96, tortuosity (α_∞) equal 1, viscous (Λ) and thermal (Λ') lengths, respectively, 30 and 70 µm.

The overframe is a 0.5 mm solid material, with $\rho = 1000$ kg/m^3, tensile modulus (E) of 0.3 GPa and Poisson's ratio (ν) of 0.49. Finally, the interior panel is a composite material containing 2 external fiberglass plies (0.2 mm thick, $\rho = 1800$ kg/m^3, $E =$ 10 GPa, $\nu = 0.2$) and an interior core (8 mm thick, $\rho = 50$ kg/m^3, $E = 0.03$ GPa, $\nu =$ 0.2). Also, a thin air gap (0.01 mm) is placed between the elements so no structural connection is considered.

The TL for the configuration presented can be seen in Fig. 12.9, together with the results for intermediate configurations. The total thickness for this case study

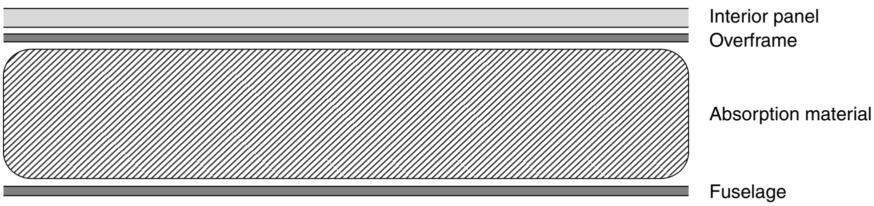


Fig. 12.8 NCT configuration considered for the case study

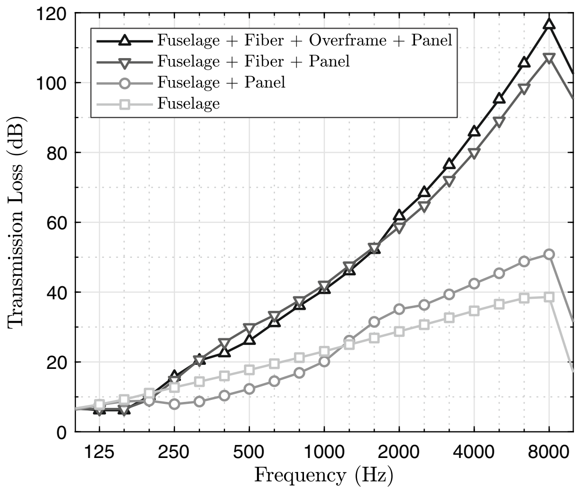


Fig. 12.9 Transmission Loss (TL) results for the case study configuration

solution is 76.7 mm. Note that solutions between 3 inches (76.2 mm) and 3.5 inches (89 mm) are typical in the aeronautic industry. The inclusion of the interior panel increases the TL at high frequencies, when comparing to the fuselage alone, but reduces it at lower frequencies due to the double wall effect.

The inclusion of the absorption fiber and the overframe significantly improves the TL at mid to high frequencies but little influence is seen at lower frequencies.

As seen in the Sect. 12.2.1 before, the aircraft engine can be responsible for low frequency excitation at the fuselage. This is also true for the TBL excitation, mainly at the aft part of the aircraft, i.e., the rear part, as it is shown in Fig. 12.4 where it is clear that the low frequency content importance increases progressively with the distance from the aircraft nose. Therefore, the results presented in Fig. 12.9 are not optimal for these sources and the design of a NCT that can act at lower frequencies is one of the main challenges to improve the aircraft acoustic comfort.

Even a simple addition of mass, which is far from desired in the aeronautic industry, may not be sufficient. For example, if the overframe density is twice the original, the TL in this case will only be affected above 1000 Hz, like shown in Fig. 12.10. That means that any mass to be added to the treatment must be optimized to give results at lower frequency.

The use of tuned resonators, as suggested by some of the papers discussed in previous sections, can provide attenuation at low frequencies even with limited space. Similar to the work presented in [14], the transmission loss for an embedded resonator array in the NCT was calculated and is presented in Fig. 12.11. For this analysis, 3 sizes of Helmholtz's resonators were used ($l_n = 0.007$ m, $l_n = 0.01$ m, $l_n = 0.012$ m), being l_n the length of the necks of the resonator, that way a broader frequency attenuation is achieved. The other dimensions were kept constant, with $D = 0.05$ m, $r = 0.0046$ m, where D is the resonators cavity diameter and r the radius of the resonators neck's transversal section.

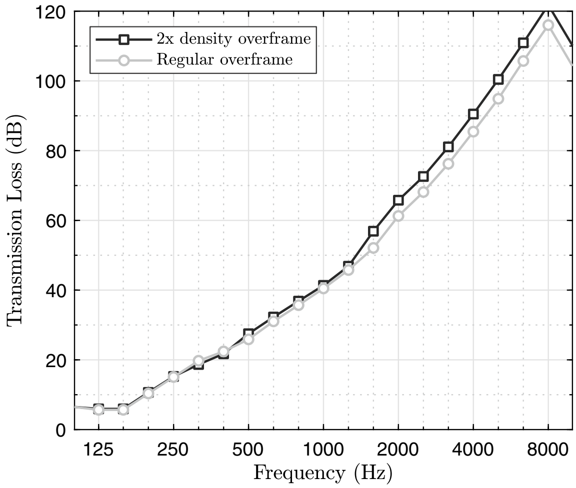


Fig. 12.10 TL results varing the density of the overframe

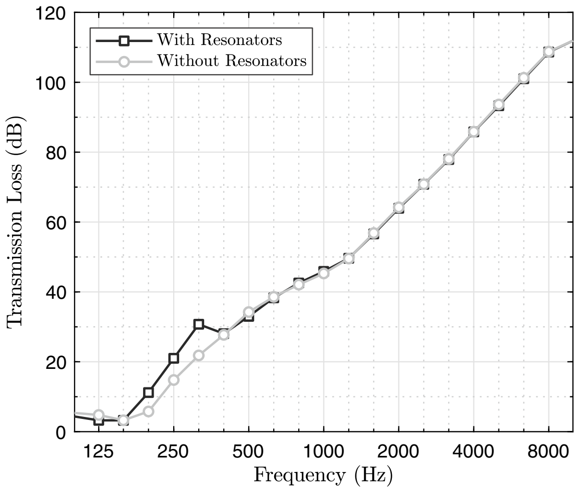


Fig. 12.11 TL results for the NCT with embedded resonators

It can be seen that up to 9 dB reduction can be obtained 300 Hz by using resonators but the influence of those are significant even in lower frequencies.

The use of resonators is an example of the potential that can be obtained by changing the current status of the noise control treatment applied to the aircraft. Variations of this concept like the use of microperforated layers, inclusions, porous design and acoustic metamaterials are solutions that present endless possibilities and can be a game changer for the industry, bringing a new perception of NVH comfort inside an aircraft.

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