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Experimental validation of acoustic metamaterials noise attenuation performance for aircraft cabin applications

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ABSTRACT

Over the past few decades, various low frequency noise control technology concepts incorporating acoustic metamaterials have been proposed in the literature. The proposed technologies showed promising performance, with a significant noise attenuation rate per thickness unit and are considered as an improved solution when compared to conventional sound insulation materials. Previously presented approaches with layered porous materials and embedded Helmholtz resonators (HR) exhibited considerable potential when tuned at tonal, multi-tonal or narrow frequency bands. In the present study, two noise control solutions were

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investigated numerically and their noise control performance was validated experimentally in single and double wall configurations when attached to a stiffened curved panel under diffuse field excitation in a sound transmission loss (STL) facility. The first solution comprised glass wool layers and a high flow resistivity micro-perforated screen for broad band noise attenuation. The second solution comprised glass wool layers with embedded HR designed to attenuate the effect of the ring frequency of the curved fuselage panel under diffuse field excitation. The paper discusses the main mechanisms involved in the STL performance of the two noise control solutions in single and double wall configurations.

1. INTRODUCTION

Aircraft cabin comfort is an important design aspect for any aircraft manufacturer. The entire travel experience for passengers and aircrew on-board an aircraft is highly determined by the comfort, efficiency and level or diversity of services available in the cabin. The overall aim of any innovative approach adopted by aircraft manufacturers is to offer travellers the quietest, most comfortable and attractive cabin environment possible. Although all aircraft manufacturers are constantly improving their cabin noise comfort standards, it is expected that new vehicle cabin designs will integrate contemporary technologically advanced concepts, optimized for low fabrication and integration costs, as well as low weight while providing an enjoyable travel environment.

The design of new aircraft cabin panels integrating noise and vibration control solutions could incorporate novel metamaterial concepts such as tunable 3D-printed small-scale resonators or complex geometry acoustic metamaterials.

The research on acoustic insulation metamaterials is relatively recent. While their great potential to attenuate sound has been demonstrated, most of the research work to date were limited to proofs of concepts at a small laboratory scale. No industrialization of such a technology for aerospace applications exists. Compared to conventional materials, acoustic metamaterials have shown a significant noise attenuation rate (dB/m), and they can be tuned at tonal, multi-tonal, or narrow band noise. In this context, the industrialization of acoustic insulation meta-material solutions in combination with conventional materials seems a promising solution to achieving cabin noise levels reduction in the low frequency range, a very challenging task when using solely conventional acoustic insulation packages, given the thickness and weight constraints in aircraft cabin design.

The main objective of the present study was to develop, fabricate, characterize and demonstrate engineered materials incorporated within existing aircraft thermo-acoustic insulation for improved cabin noise reduction. Moreover, the proposed solution had to be optimized not only for acoustic performance but also for low weight, and low fabrication costs. The challenge was therefore to select a concept that, through multi-variable optimization, would produce a noise reduction improvement and would rapidly reach a technology readiness level for integration on-board aircraft. Two different concepts were investigated. The first solution aimed at adding to the existing insulation package a high flow resistivity micro-perforated screen for broad band noise attenuation. The second solution consisted of embedding Helmholtz resonators (HR), in the insulation package, optimized to attenuate the effect of the ring frequency of the curved ribbed fuselage panel under diffuse field excitation. The design and optimization of the HR were based on the study of the state of the art on the topic.

A comprehensive literature review of acoustic metamaterials design and achieved performance, highlighting unusual acoustic properties, providing examples of engineered materials resulting in manipulations of audio-frequency airborne sound as well as providing an overview of future directions in the field was published by S.A. Cummer et al. [1] in 2016. Despite the large diversity of methods presented in the review, the authors pointed out however the remaining challenge of developing efficient techniques for the fabrication of large-scale metamaterial structures in order to translate laboratory experiments into technologies that could be integrated in real life applications. The configuration of acoustic resonators integrated in the insulation blanket of the aircraft cabin sidewall was studied by H.L. Kuntz et al. [2]. The influence of the sidewall thermal-acoustic insulation on the performance of the resonators was demonstrated through laboratory and in-flight testing on-board a PTA Gulfstream II aircraft. In-flight additional 5-6dB noise reduction attributed to the resonators was observed. Similarly, Doutres et al. [3] studied and experimentally validated the performance of sound insulation configurations of acoustic resonator inclusions within a porous material. The authors demonstrated that the proposed design improved the sound attenuation at low frequencies while maintaining an acceptable acoustic treatment thickness. The acoustic characteristics of Helmholtz resonators with the cavity lined with acoustically absorbing material have been studied by A. Selamet et al. [4]. The study demonstrated using analytical, numerical and experimental methods, the effects of both the thickness and the resistivity of fibrous material on the resonance frequency and acoustic attenuation. E. Gourdon et al. [5] investigated the influence of non-linear tailored shapes of a Helmholtz resonator neck on the sound absorption coefficient. Moreover the performance of micro-perforated panels backed by Helmholtz resonators with various neck shapes were studied by S-H Park [6] to assess their low-frequency normal incidence sound absorption performance. The resonator neck extension length versus spiral neck configurations were studied by C. Cai et al. [7]. It was demonstrated that the increase in the neck extension length resulted in a shift towards the low frequencies of the resonance frequency and a band narrowing of the sound transmission loss peak. Moreover the sound transmission loss of the 4 turns spiraling neck configuration was shown to provide an interesting sound attenuation performance and a 30Hz drop of the resonant frequency peak. The sound absorption performance and the design of an open neck acoustic resonator with flexible hollow tubes for low frequency absorption was studied by F. Simon [8]. The author demonstrated the low frequency improvement and the influence of the length of the tubes on the sound absorption coefficient of configurations with perforated plate backed by a cavity (no tubes) versus configurations where tubes of various lengths were connected to the perforations. Helmholtz resonators array performance was studied by C. Cai et al. [9]. P. Leclaire et al. [10] presented a theoretical and numerical study of the sound propagation in air-saturated porous media with straight main pores bearing lateral cavities (dead-ends). The model predictions were compared with experimental results and possible designs of materials with thicknesses of a few centimetre displaying enhanced low frequency absorption at a few hundred hertz were proposed. Moreover, T. C. Kone et al. [11, 12] presented the design and the acoustic properties of complex shape metamaterials using a numerical Thermo-Visco-Acoustic (TVA) model to simulate the acoustic behaviour of the periodic cells composing the metamaterial. The modeling and experimental investigation of a HR with a flexible end plate was proposed by S. S. Nudehi et al. [13]. A. Sanada et al. [14] proposed a two-degree-of-freedom HR design with a flexible mid-cavity panel to extend the frequency range of the sound absorber. Moreover, A. Abbad et al. [15] presented a numerical and experimental investigation on the acoustic performance of membraned HRs embedded in a porous matrix. The authors demonstrated the low frequencies transmission loss performance of the proposed design along with some sound absorption performance degradation due to the membrane resonance frequency. However, these negative effects were shown to result in a significant improvement of the sound transmission loss at medium and high frequencies.

The literature review presented in this section, far from being comprehensive, is aimed at evaluating the performance and the feasibility of diverse concepts for an eventual large scale implementation on-board an aircraft. The literature review allowed for the selection of a relatively simple geometry Helmholtz resonator solution as it was obvious that the more complex the metamaterial design the more expensive and likely heavier, without mentioning that a higher dispersion in the expected performance was anticipated due to inherent fabrication imperfections.

2. PARAMETRIC STUDY

A parametric study was conducted to assess the influence of different geometrical features of the HR on the normal incidence Sound Transmission Loss. Numerical Finite Element (FE) simulations were conducted using the commercial software Simcenter3D. The investigation concentrated first on the influence of the shape of the neck on the acoustic performance of the HR. Several neck shapes were considered and three of them are presented here. Their geometrical properties are shown in Figure 1a. The volumes of the cavity and of the neck were kept constant. The three neck shapes "Straight", "Taper" and "Hourglass" considered here and their 3D geometry are shown in Figure 1. Their dimensions were optimized so that the volume of each neck be constant. All HR cavities had the same diameter *D* and length *L*. The air layer surrounding the HR cavity had a thickness of 10 mm. Johnson Champoux Allard's equivalent fluid model [16] was used to accurately account for the viscous dissipation in the HR neck. However, for the complex neck shape of the "Taper" and "Hourglass" configurations, the neck was discretized in multiple segments (perpendicular to the axis of revolution of the neck) and the average diameter of each segment was used to accurately estimate the equivalent fluid properties. This discretization is shown in Figure 1b as the various blue gradation segments along the length of the neck.

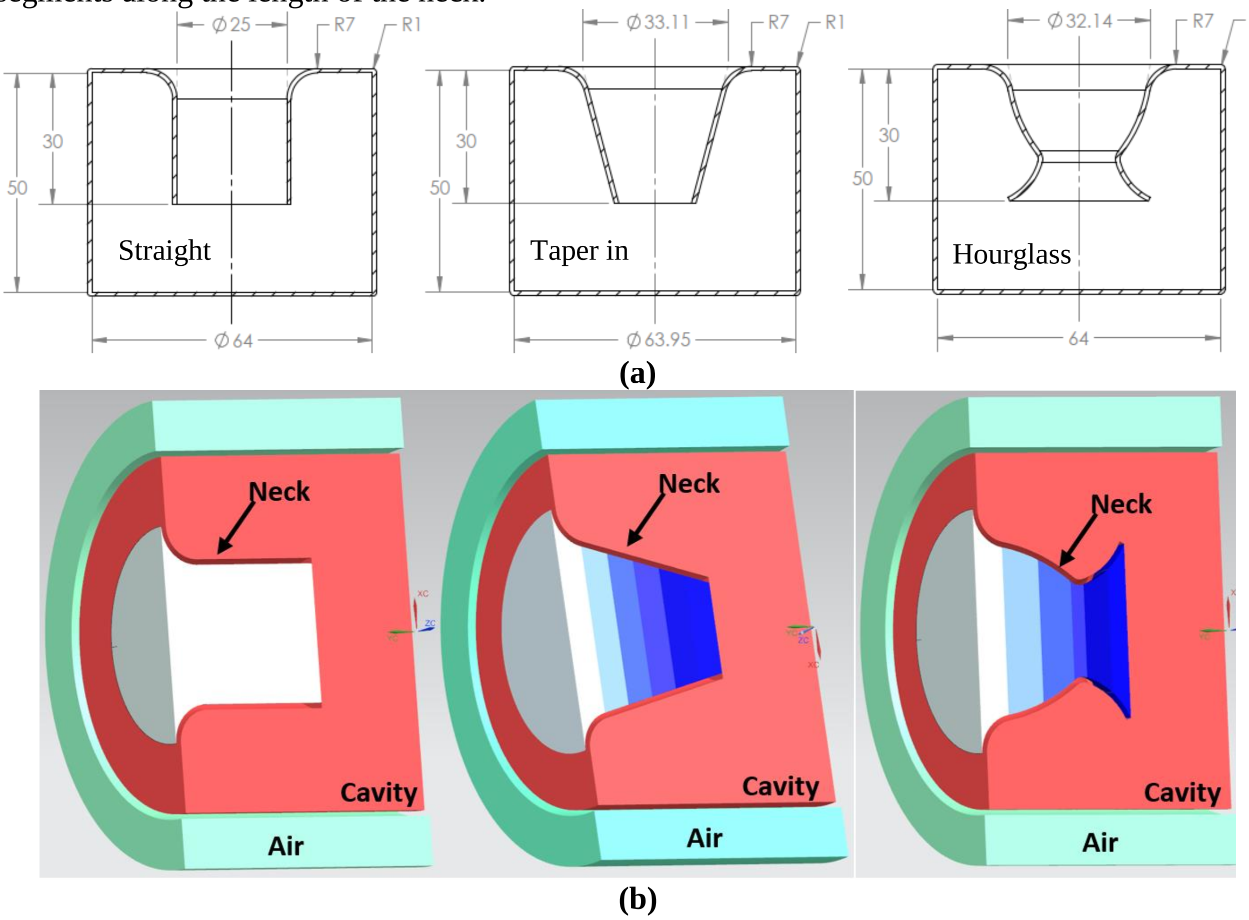


Figure 1: The dimensions (a) and the 3D geometries of the Helmholtz resonators (b)

The normal incidence Sound Transmission Loss of each configuration is shown in Figure 2. It can be observed that the complex shape neck HRs have a very good performance at a resonant frequency 44 Hz below the "Straight" neck configuration.

The influence of the neck radius R_n was investigated on a HR with a cavity length of L_c=50 mm, and radius of R_c=50 mm. The length of the neck was L_n=15 mm. The normal incidence Sound Transmission Loss of the HR embedded in a layer of fiberglass wool was calculated in a configuration simulating an impedance tube set-up. The radius of the tube was 60 mm. The normal incidence Sound Transmission Loss finite element results are shown in Figure 3. It can be observed that the resonance frequency and the STL of the HR decrease with the decrease of the neck radius. The influence of the neck length L_n was investigated as well on a HR with a cavity length of L_c=50 mm, and radius of R_c=50 mm. The radius of the neck was R_n=15 mm. The normal incidence Sound Transmission Loss finite element results are shown in Figure 4. It is worth mentioning that the resonance decreases, in amplitude and frequency, as the diameter of the neck decreases, or as the length of the neck increases. Those observations are important as they clearly demonstrate that lower resonant frequencies of the

HR can be achieved by tailoring the dimensions of the neck without increasing the dimensions of the HR.

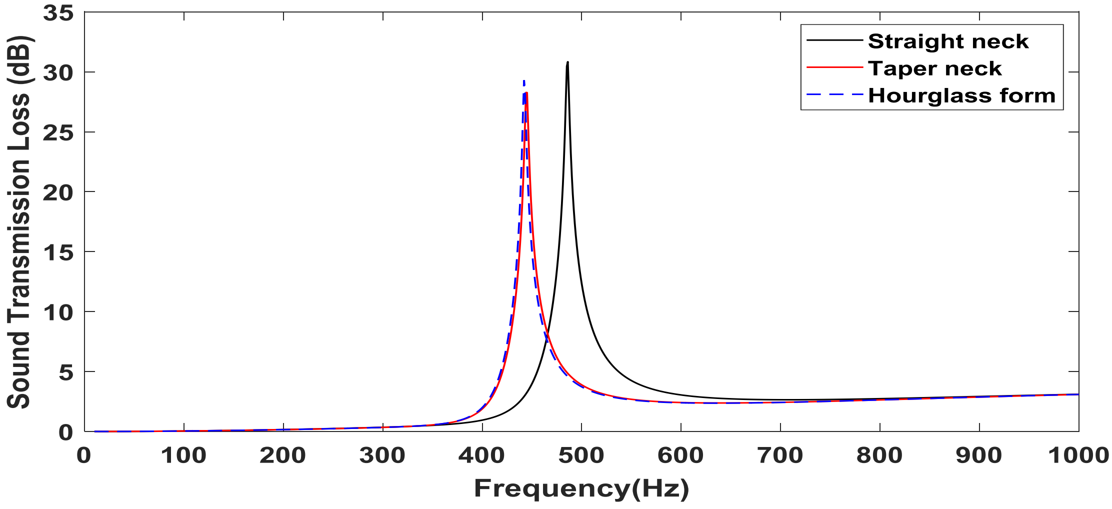


Figure 2: Influence of the neck shape on the Sound Transmission Loss

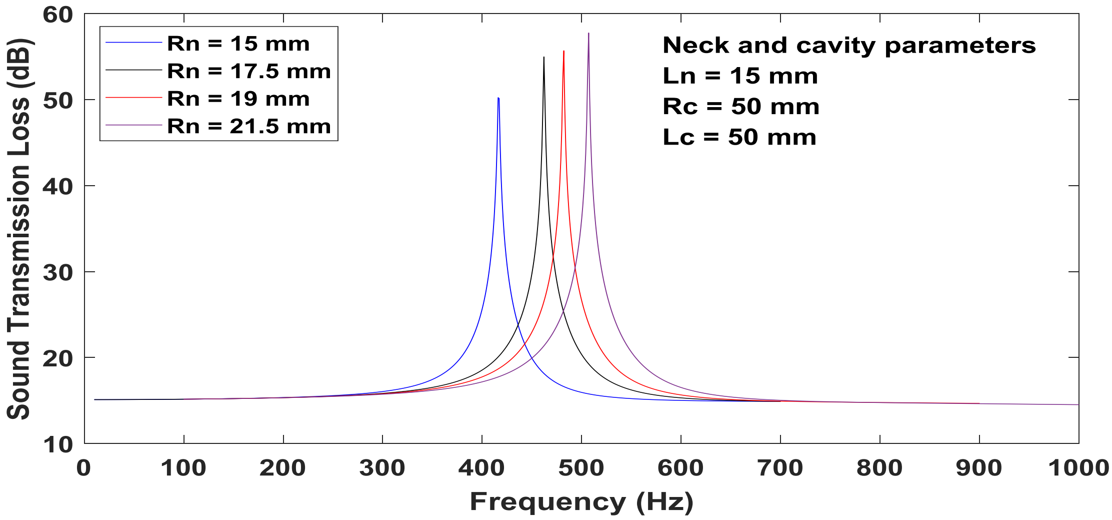


Figure 3: Influence of the neck radius on the Sound Transmission Loss

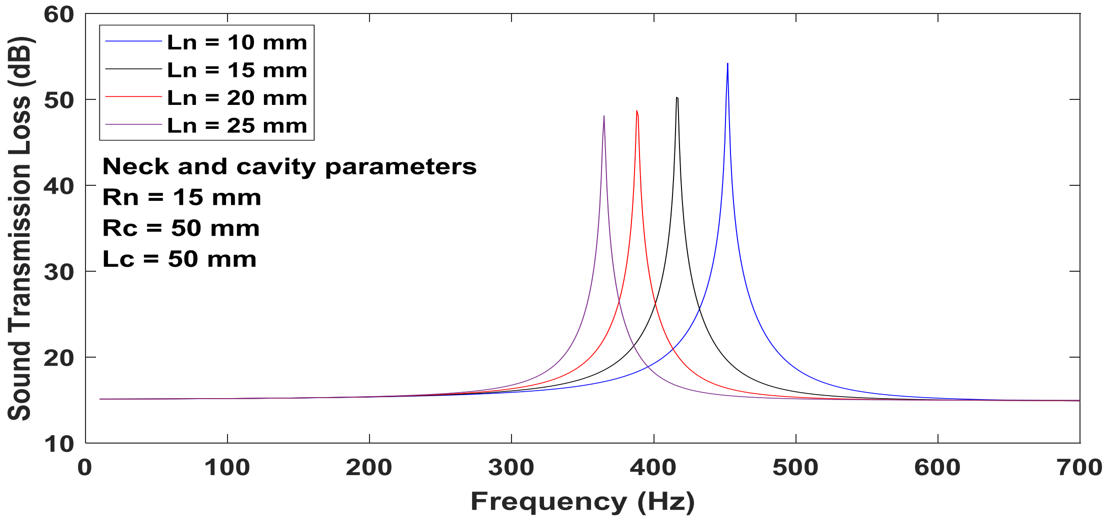
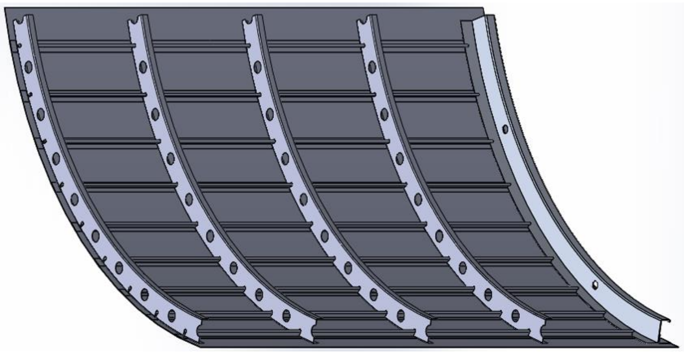


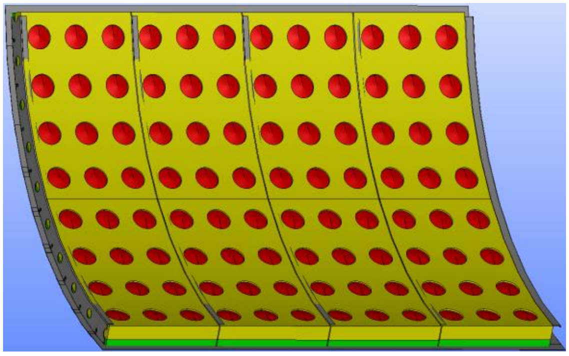
Figure 4: Influence of the neck length on the Sound Transmission Loss

3. EXPERIMENTAL RESULTS

Two acoustic insulation configurations were integrated in a representative aircraft fuselage section and tested under a diffuse field excitation using the Sound Transmission Loss facility at the Université de Sherbrooke. The lateral dimensions of the stiffened panel were 1.7 m by 1.39 m. The panel was made of an Aluminium skin with a thickness of 1.5 mm and comprised nine longitudinal and five lateral stiffeners as shown in Figure 5 (a). The fuselage section had a radius of 1.34 m and a ring frequency of 670 Hz.



(a)



(b)

Figure 5: The stiffened panel :(a) SolidWorks 3D model; (b) panel with 96 resonators embedded in a 2" fiberglass layer (YELLOW: fiberglass wool; RED: Resonators)

The first acoustic insulation solution comprised fiberglass layers and a high flow resistivity micro-perforated screen (APF) for broad band noise attenuation. The micro-perforated screen used in this project was a development sample material provided by 3M Company: APF 3M 2018-2300. The properties of the micro-perforated screen (APF) development sample and Fiberglass are provided in Table 1. A comparison of the STL measured for the various configurations tested in a single wall set-up are shown in Figure 6.

Table 1: The properties of the Fiberglass and the micro-perforated screen

	Thickness (mm)	Density (Kg.m-3)	Porosity (%)	Flow Resistivity (Ns.m-4)	Tortuosity	L.C.V (µm)	L.C.T (µm)
APF 3M 2018-2300	0.36	811	1.1	6182352	1	45.5	45.5
Fiber Glass 0.42pcf	25.4	6.72	86	20709	1	84.8	170

Note: LCV and LCT are the Viscous and Thermal Characteristic Lengths respectively.

The STL of the bare stiffened panel, the panel with a 2" layer of fiberglass wool and two configurations comprising an APF layer are compared. It can be observed that due to the high flow resistivity of the APF film, a significant improvement in the STL was achieved when compared to the configuration Panel with 2" of Fiberglass wool. Moreover, the configuration of APF sandwiched between 2 layers of 1" fiberglass wool provided an improvement in the STL at medium to high frequencies while the configuration Panel with 2" of fiberglass wool and APF provided an improvement in the STL at low to medium frequencies. In order to better visualize the achieved noise attenuation, the insertion loss of Panel with 2" of fiberglass wool and APF versus Panel with 2" of fiberglass wool as well as APF sandwiched between 2 layers of 1" fiberglass wool versus Panel with 2" of fiberglass wool are shown in Figure 7.

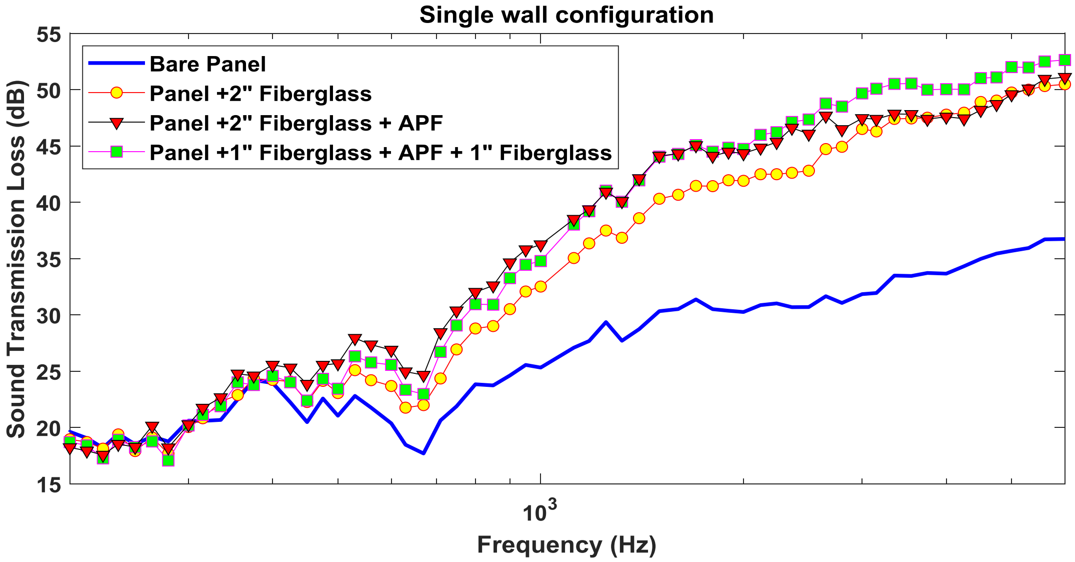


Figure 6: The Sound Transmission Loss of the stiffened panel with Fiberglass and APF layers

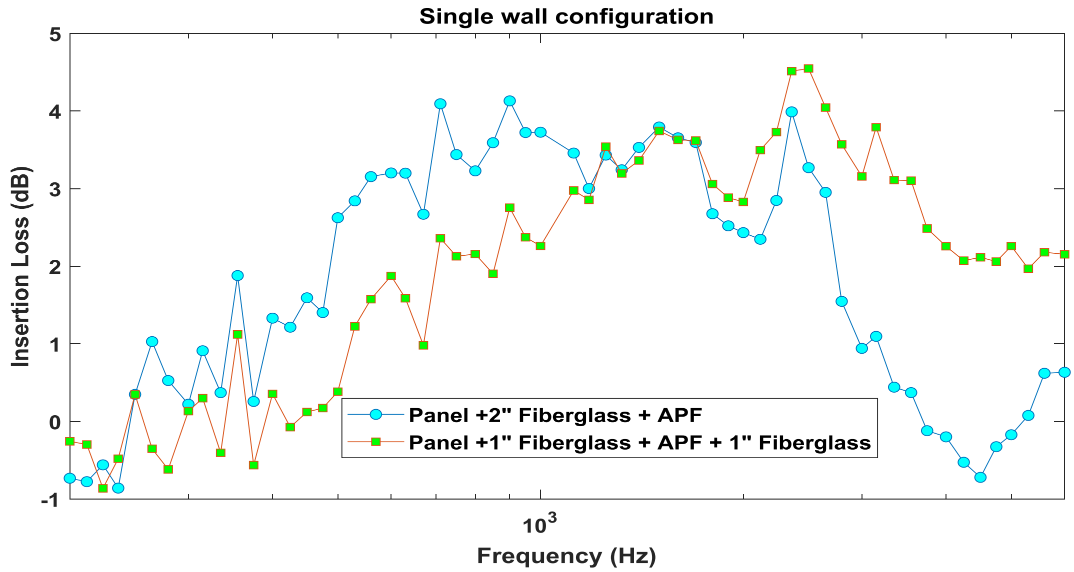


Figure 7: The Insertion Loss of the stiffened panel with Fiberglass and APF layers

The acoustic insulation solution was tested as well in a Double Wall configuration. In order to obtain the Double Wall configurations, a honeycomb panel with a thickness of 7 mm was added to the Single Wall configurations. The honeycomb panel was mounted at 120 mm from the skin of the fuselage. As for example a single wall configuration (Panel+2" Fiberglass) was compared in the present investigation to the corresponding double wall configuration (Panel + 2" Fiberglass + Honeycomb) to assess the performance (insertion loss) of the acoustic insulation treatment. The STL results are shown in Figure 8. It can be observed that the significant improvement in the STL achieved with this solution in the single wall configuration, seems to be lost completely in a double wall configuration. This demonstrates the great importance of demonstrating the noise attenuation performance of the acoustic insulation designs in configurations closely replicating the real-life integration conditions.

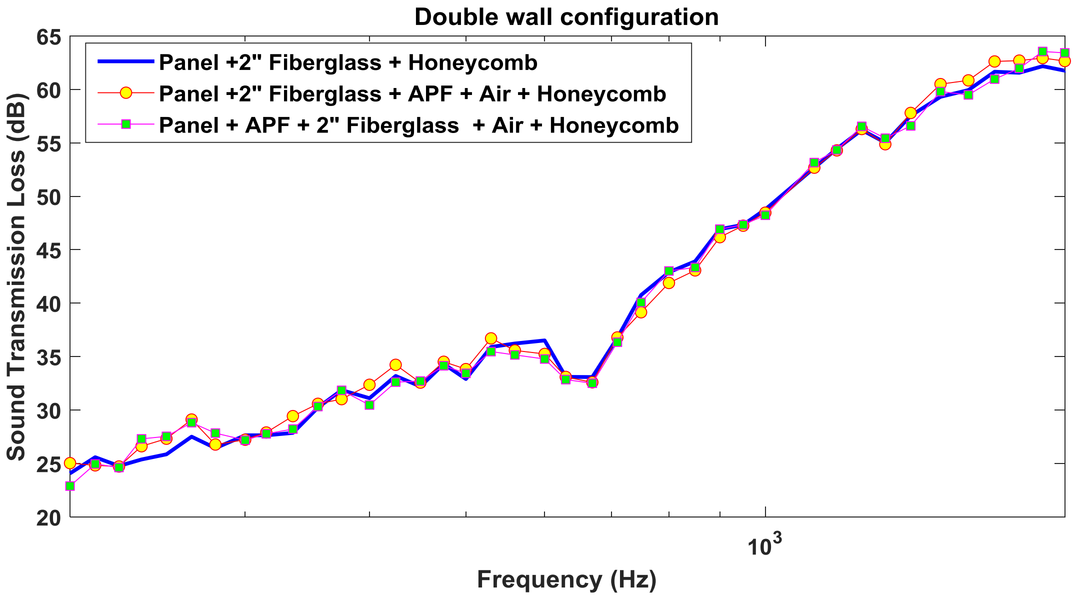


Figure 8: The Sound Transmission Loss of the stiffened panel with Fiberglass and APF layers in Double Wall configuration

The second acoustic insulation solution comprised glass wool layers with embedded HR designed to attenuate the effect of the ring frequency of the curved fuselage panel under diffuse field excitation, as shown in Figure 5 (b). The characteristics (resonance frequency and geometrical parameters) of the HR are provided in Table 2.

Table 2: The characteristics of the Helmholtz resonator

	Resonance Frequency **(Hz)**	Cavity Diameter **(mm)**	Cavity Length **(mm)**	Neck Diameter **(mm)**	Neck Length **(mm)**
Resonator A	670	80	50	50	20

It is worth mentioning that based on the parametric study observations, the geometry of the resonator neck was optimized to improve the viscous dissipation. Therefore, the neck of the HR considered in this investigation had an elliptical cross-section.

The configuration of stiffened fuselage section with a 2” layer of fiberglass wool and 96 embedded HRs was first tested in a Single Wall set-up. Note that the HRs structure has been optimized to minimize the added weight inherent to a robust integration into the sound package. The area covered by the 96 HRs embedded in the fiberglass layer represented 32% of the panel surface. The relative added mass of the resonators compared to the mass of the panel was 15%. The diffuse field Sound Transmission Loss results are shown in Figure 9. When compared to the baseline configuration e.g. Panel with a 2” layer of fiberglass, a significant improvement of more than 4.5 dB was observed in the STL in the ring frequency region due to the addition of the 96 HRs. It is worth mentioning that when compared to the baseline configuration it is clear that the achieved noise attenuation performance is not attributed to the added mass of the HRs but due to their acoustic designed characteristics. An added mass effect would have been observed in the frequency range above the ring frequency when compared to the baseline. This demonstrates that the HRs were well isolated from the main structure and acted only as acoustic inclusions.

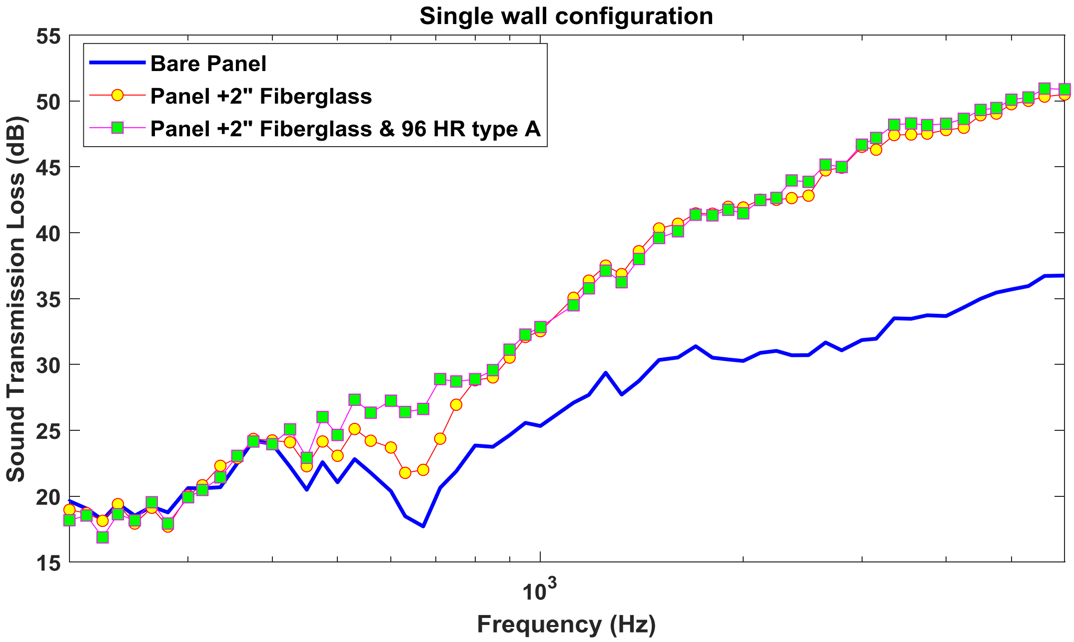


Figure 9: The Sound Transmission Loss of the stiffened panel with a Fiberglass layer and 96 embedded Helmholtz resonators – Single Wall configuration

The acoustic insulation configuration was tested as well in a Double Wall set-up. The diffuse field Sound Transmission Loss results for this configuration are shown in Figure 10. In order to better visualize the achieved noise attenuation, the insertion loss of the Single and Double Wall configurations were calculated and the results are shown in Figure 11. The baseline for the Single Wall configuration was Panel + 2" of Fiberglass while the baseline for the Double Wall configuration was Panel + 2" of Fiberglass + Honeycomb. It can be observed that the acoustic insulation solution proposed here provides an additional 4.6 dB noise attenuation in Single Wall and 3.3 dB noise attenuation in Double Wall configuration, at the ring frequency, when compared to the baseline. This performance could be further improved by increasing the area ratio covered by the Helmholtz resonators while improving the design to reduce their weight.

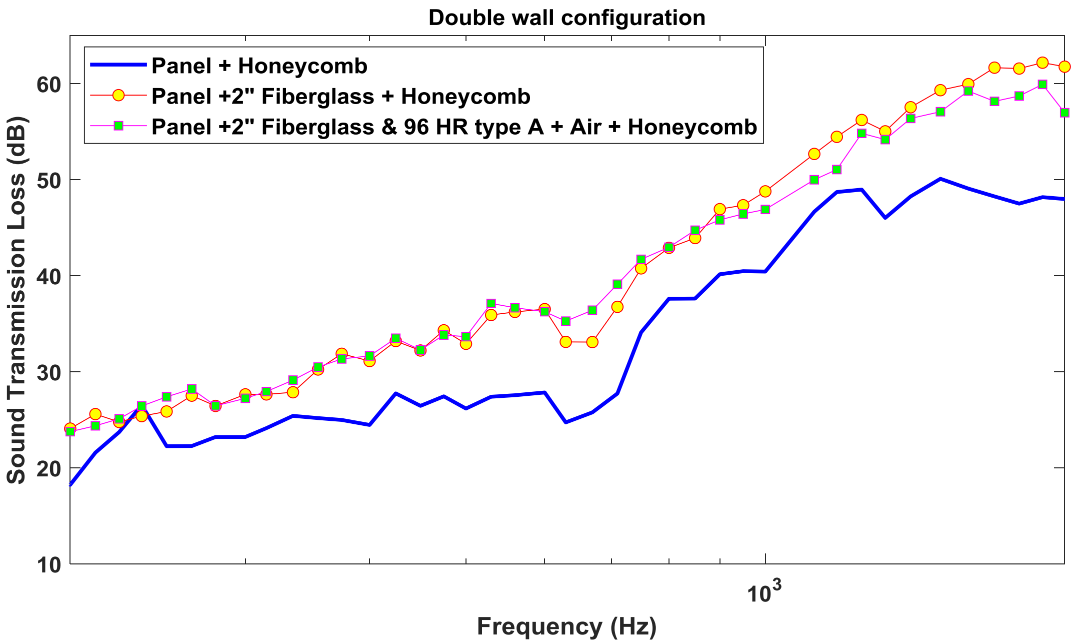


Figure 10: The Sound Transmission Loss of the stiffened panel with a Fiberglass layer and 96 embedded Helmholtz resonators – Double Wall configuration

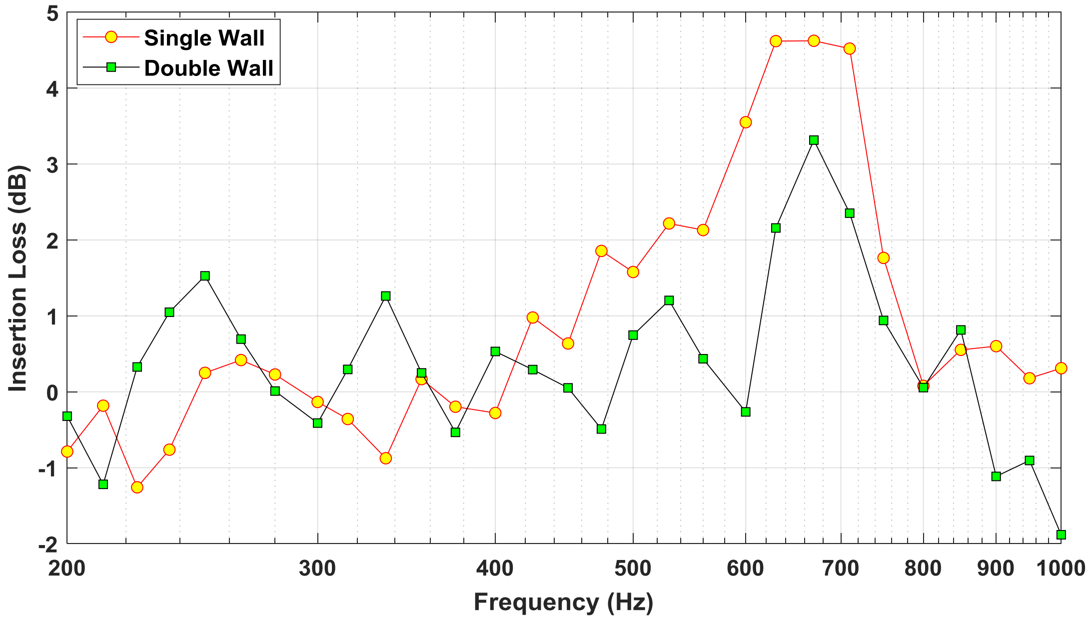


Figure 11: The Insertion Loss of the stiffened panel with a Fiberglass layer and 96 embedded Helmholtz resonators – Single vs. Double Wall configurations

4. CONCLUSIONS

The present investigation focussed on two inexpensive, light and simple to integrate noise control solutions that would allow an improvement in the aircraft cabin noise attenuation. Numerical simulations were performed in a normal incidence set-up to characterize the sensitivity of the Sound Transmission Loss to the Helmholtz resonators geometrical characteristics. The acoustic performance of the two noise control solutions was validated experimentally in single and double wall configurations when attached to a stiffened curved panel under diffuse field excitation in a sound transmission loss (STL) facility. The first solution comprised glass wool layers and a high flow resistivity micro-perforated screen for broad band noise attenuation. It was observed that broadband noise attenuation can be achieved with this solution in a Single Wall design due to the high flow resistivity of the perforated screen. However, this configuration was shown to be ineffective in a Double Wall design, representative of an aircraft cabin sidewall. The second solution comprised glass wool layers with embedded HR designed to attenuate the effect of the ring frequency of the curved fuselage panel under diffuse field excitation. The noise attenuation performance of the proposed solution, in Single and Double wall set-ups, was demonstrated through tests in a transmission loss facility under diffuse field excitation. A more comprehensive presentation of the parametric studies and the diverse acoustic solutions designed and compared as part of this project will be provided as part of journal articles presently under preparation.

6. ACKNOWLEDGMENT

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7. REFERENCES

[1] Cummer, S., Christensen, J. and A. Alù, A. Controlling sound with acoustic metamaterials. Nat Rev Mater 1, 16001 (2016).
[2] Kuntz, H. L., Gatineau, R. J., Prydz, R. A. and Balena, F. J. Development and testing of cabin sidewall acoustic resonators for the reduction of cabin tone levels in propfan-powered aircraft, NASA Report 4388, 1991.
[3] Doutres O., Atalla N. and Osman H., Transfer matrix modeling and experimental validation of cellular porous material with resonant inclusions, J. Acoust. Soc. Am. 137(6), 3502-3513 (2015).
[4] A. Selamet, M. B. Xu, and I.-J. Lee, Helmholtz resonator lined with absorbing material, J. Acoust. Soc. Am. 117(2), 725-733 (2005).
[5] E. Gourdon, A. T. SavadKoohi, Nonlinear Structuring of Helmholtz Resonators for Increasing the Range of Sound Absorption, Proceedings of Euro-Noise 2015.
[6] Soon-Hong Park, Acoustic properties of micro-perforated panel absorbers backed by Helmholtz resonators for the improvement of low-frequency sound absorption, Journal of Sound and Vibration 332(20), 4895-4911 (2013).
[7] C. Cai, C-M. Mak, X. Shi, An extended neck versus a spiral neck of the Helmholtz resonator, Applied Acoustics, Vol. 115, 74-80, 2017.
[8] F. Simon, Long Elastic Open Neck Acoustic Resonator for low frequency absorption, Journal of Sound and Vibration, 421, 1-16, 2018.
[9] Chenzhi Cai, Cheuk Ming Mak, Acoustic performance of different Helmholtz resonator array configurations, Applied Acoustics, Vol. 130, 204-209, 2018.
[10] P. Leclaire, O. Umnova, T. Dupont, R. Panneton Acoustical properties of air-saturated porous material with periodically distributed dead-end pores, J Acoust Soc Am, 137 (4), pp. 1772-1782,2015.
[11] T. C. Kone, R. Panneton, and T. Dupont, "Thermo-Visco-Acoustic Metamaterials to Damp Acoustic Modes in a Complex Geometry", *26th International Congress on Sound and Vibration*, 7-11 July 2019, Montreal, Canada.
[12] T. C. Kone, R. Panneton, T. Dupont, and S. Ghinet, "Thermal-visco-acoustic metamaterials to damp acoustic modes in complex shape geometries at low frequencies", submission process in JASA (2020).
[13] Nudehi, S. S., Duncan, G. S., and Farooq, U., Modeling and Experimental Investigation of a Helmholtz Resonator With a Flexible Plate. ASME. J. Vib. Acoust. 135(4), 2013.
[14] A. Sanada, N. Tanaka, Extension of the frequency range of resonant sound absorbers using two-degree-of-freedom Helmholtz-based resonators with a flexible panel, Applied Acoustics, Vol. 74(4), 509-516, 2013.
[15] A. Abbad, N. Atalla, M. Ouisse, O. Doutres, " Numerical and experimental investigations on the acoustic performances of membraned Helmholtz resonators embedded in a porous matrix", Journal of Sound and Vibration, Volume 459, 2019.
[16] Jean-F. Allard and N. Atalla, Propagation of Sound in Porous Media: Modeling Sound Absorbing Materials, 2nd ed. (Elsevier Applied Science, New York, 2009.