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An Experimental Investigation of the Influence of Excitation, Damping, and Sound Insulation on Sound Radiation and Transmission

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Abstract. *Increasing the level of acoustic comfort inside the cabin has been a significant issue for the market-leading aircraft and their manufacturers. The noise level in the cabin is mainly induced by the structural vibration of panels that make up the sidewall, ceiling, and floor, having engines and turbulent airflow around the aircraft as the primary external sources of excitation. Although the vibroacoustic study of panels is a well-known topic and widely explored in the literature, it maintains relevance due to its diverse applications in different conditions. This paper proposes the study of the relationship between radiation efficiency, damping, the use of porous materials, and the type of excitation on the vibroacoustic behavior of different aeronautical panel systems. The study is conducted from a series of measurements of transmission loss, radiation efficiency, and damping loss factor performed in reverberation and semi-anechoic rooms. The influence of those parameters on the panel's response is discussed: how resonant and non-resonant modes contribute to sound radiation and how the inserted damping acts over the response spectrum. The evaluation is done using a variety of system configurations, containing four types of stiffened panels, four types of sound insulation material, including glass fibers and polymer foams, a honeycomb trim panel, and viscoelastic patches, subjected to two types of excitation: punctual force and diffuse sound field. Through the analysis of the obtained data, it is noted, for example, that the efficiency of noise and vibration treatment depends on the type of excitation, that the porous material inserts damping in the panel in the spectrum range below the coincidence frequency, and that the increase in the radiation efficiency might counter-intuitively mean in reducing cabin noise. The conclusions of this study help in the design decision-making process of aeronautical panels and acoustic treatment according to the specificities of each application.*

Keywords: *Vibroacoustics, Sound Transmission Loss, Radiation Efficiency, Damping loss factor*

1. INTRODUCTION

The study of how to improve the acoustic comfort inside the cabin has been a combination of numerical and experimental efforts for the last decades. Normally, the experimental data are used as input for numerical models of transmission loss or sound radiation, using methodologies such as SEA or FEM to compute the expected interior sound pressure level due to a particular excitation. In this context, this study aims to present a series of measurements of fuselage panels under different setups in a laboratory environment, to endorse numerical models by providing input data and physical interpretations, and to understand the influence of such setups over the panel acoustic performance. For an aircraft fuselage, the transmission loss factor, the radiation efficiency, and the damping loss factor are among the most important parameters to be assessed during an experimental measurement, in which the acoustical parameters are characterized for the materials. These are the parameters that will be analyzed in this study.

In most cases, fuselage panels have frames and stringers on one of their sides to fulfill the structural requirement in the aircraft. However, the consequence of this configuration is that the panel improves its sound efficiency. To overcome this problem, viscoelastic material is typically applied on the interior surface of the fuselage, increasing the structural damping and, consequently, reducing the propagated noise. When adding this new element to the fuselage surface, the dynamic behavior of the panel is changed. This behavior also occurs with the addition of porous materials in conjunction with a single panel. Both these behaviors will be better evaluated throughout this study. For the porous materials used for passive acoustical control, Cummings (2001) and Tomlison (2004) present that their presence increases the damping of a vibrating plate when in contact or very close to its surface. The porous material has lower radiation impedance comparing with the air, below the critical frequency of the panel, increasing the radiation efficiency of the plate and the radiated energy dissipation for this same frequency range. In addition, the energy that is radiated to the interior of the porous material is dissipated as a function of the wavelength. The vibration energy dissipation from the plate can be also associated with the fact that, in frequencies below the critical frequency, the molecules in the close field, moving along the elliptical trajectory near the plate, are dissipated by visco-thermal effects when they interact with the porous materials, according to the same authors.

Regarding the acoustic concepts applied in this study, Fahy and Gardonio (2007) presents the ratio τ_∞/τ_r, in which both components represent the method where a finite partition transmits energy: τ_∞ is the transmission coefficient of an infinite partition - mass-controlled or non-resonant transmission -, and τ_r is the transmission coefficient related with the resonant models. Some of the key parameters of the structure are related to this ratio, such as the damping, the panel superficial area, and the critical frequency. As these parameters increase, so does the ratio τ_∞/τ_r.

The excitation will also present a major impact on the behavior of the plate, since the punctual force acts predominantly on resonant modes, while the acoustic field acts also on the non-resonant modes. For an aircraft in cruise flight condition, the major excitation over the fuselage is the Turbulent Boundary Layer (TBL), which has different characteristics when compared with the Diffused Acoustic Field (DAF) - a typical excitation used in laboratory environments. Therefore, two different excitations were used in this study: an acoustic excitation (DAF), and a mechanical one (punctual load using a shaker), to assess the influence of the excitation over the vibroacoustic behavior of the studied system (Marchetto *et al.* (2017, 2018); Arguillat *et al.* (2010); Maury *et al.* (2002)).

Considering the fuselage panel of this study, besides the baseline configuration, other three will be assessed: one baseline panel with the increase of the skin thickness, one baseline panel with chemical machining - reducing its thickness -, and one last panel with three frames. Regarding the acoustic treatment material, four porous materials will be assessed, applied as a thermoacoustic treatment on the single panel: fiberglass 0.6 pcf, fiberglass 1.2 pcf, melamine 0.6 pcf, and melamine 0.3 pcf. The purpose of this study is to present a brief description of each experiment, together with the experimental procedures, the exposition of results, and discussion.

2. MEASUREMENTS SETUP

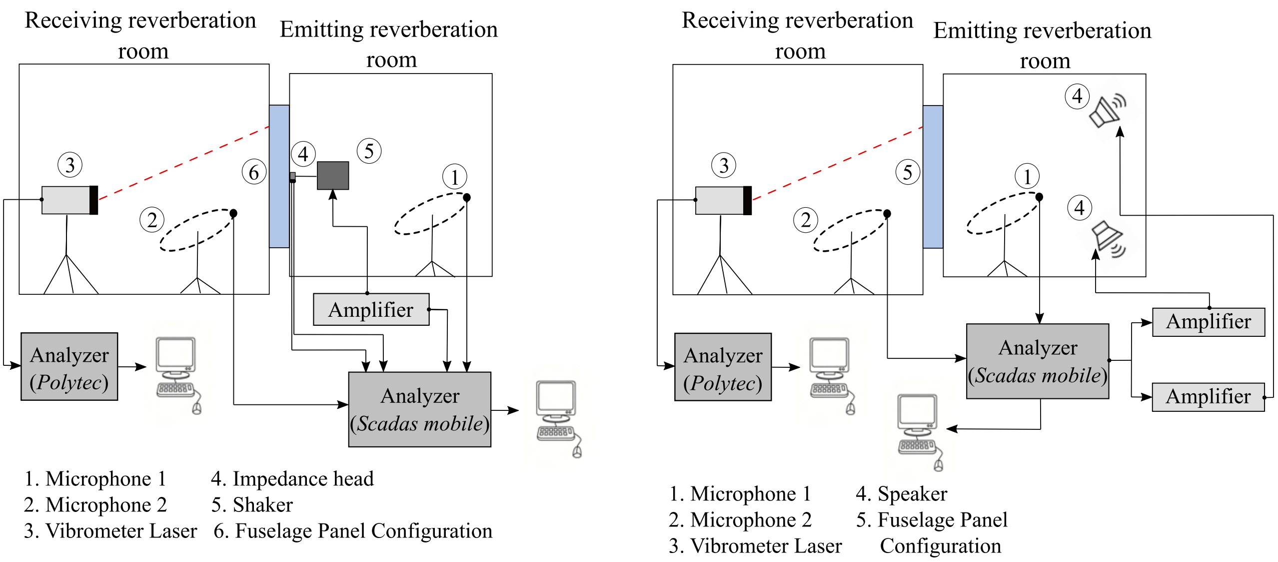
In this study, 12 different configurations will be measured, each of them was assembled with the assistance of a steel frame in an aperture of 1.80 m height and 1.13 m width between two reverberate chambers: the emitting, with 150 m^3, and receiving, with 200 m^3, reverberation rooms. Both have a Schroeder frequency of 200 Hz. The only exception in this assemble is regarding samples 5 and 11, in which a honeycomb panel with the same dimensions of the aperture was used, without the steel frame. In addition, plasticine clay was used to enclose acoustic leakage in both chambers. All configurations of panels were assembled as presented in Fig. 1(a), where the packed patches are built with rectangular porous material overlap layers until the sample reaches approximately 76 mm thickness. They are covered with impervious film and embedded in the bays, and positioned on the emitting reverberation room side of the panel. For the honeycomb panel (configuration 11), the assembly setup is shown in Fig. 1(d), in which a steel frame was build using porous materials packed patches with dimensions alike to the metal frames from fuselage panels.

Inside each reverberation room, two types of excitation were evaluated: mechanical load (using an electrodynamic shaker) and acoustic diffuse field. Figure 1(d) also presents the setting of the shaker using steel cables. Besides, an impedance head is used, connected to the shaker with white noise as input. Due to the limitation of the shaker to inject energy in high-frequency bands, two separated frequency ranges are used: from 0 to 2k Hz, and from 1.6k Hz to 10k Hz, due to the limitation of the shaker to inject energy in high-frequency bands. The acoustic diffuse field, on the other hand, is settled using two speakers at each corner of the chamber, also having a white noise signal as input between 0 and 10k Hz.

The laser vibrometer (Polytec PSV-500 Scanning head) was positioned in the receiving reverberation room with its analyzer and computer and, after measuring the vibration and turning off the laser vibrometer, the background noise was measured. On the surface of the panel, a rectangular grid was built with 375 points, where the velocity of the panel was measured using an average of five measurements for each point. For the honeycomb panel configurations, however, it was observed that for the cases in which the honeycomb panel was measured, it offered difficulties in obtaining the answer, because the reflection of the laser beam was not specular enough to guarantee a strong reading signal by the vibrometer. The signal quality detection was improved by applying non-aqueous developer spray paint on the honeycomb panel surface, as presented in Fig. 1(b). Regarding the input and output signals in the measurement setup, Fig. 2 presents a representation of the measurement chain considering shaker and DAF as the excitation source on a single panel, respectively.

(a) (b) (c) (d)

Figure 1. a) Position of the isolators on the fuselage panel, and the setup for the porous material packed patches on the fuselage panel. Assembly of a fuselage panel configuration in the setup with laser vibrometer: b) view from the receiving reverberation room; c) view from the emitting reverberation room; d) shaker positioned on the porous material side panel.



(a) (b)

Figure 2. a) Setup with laser vibrometer, and b) Setup with DAF.

Following the previously presented setup, all configurations for a single panel with porous material are shown in Tab. 1 For each porous material, two thicknesses were selected for each sample, and their acoustic absorption coefficients were measured using an impedance tube by normal incidence, as well established by Allard (2009) and Mareze (2013). An inverse characterization was performed and the results for each material are presented in Tab. 2.

3. RESULTS AND DISCUSSION

Before presenting the measurement results, some considerations must be made concerning the fuselage panels, the excitations, and the data. Regarding the panel configurations with bigger thickness and with chemical machining, these two variations will have lower and higher critical frequencies than the baseline panel, respectively. Moreover, for the fourth panel with the same thickness as the baseline panel but with three frames, the superficial areas of the panel bays have the same impact as increasing the total surface area of the panel. About the excitations, a punctual mechanical load excites the plate closer to a TBL than a DAF, and from the mathematical point of view, it can be said that when converting the pressure field from this excitation to the spatial domain, using the Fourier Transform, the TBL spectrum can be better correlated to punctual load spectrum than to DAF excitation (Chevillotte *et al.* (2015)). In addition, it is important to

Table 1. Test Matrix with the measured configurations, where for the Fuselage column, a) Baseline fuselage panel, b) Fuselage panel with thick skin, c) Fuselage panel with three frames, and d) Fuselage panel with chemical machining.

#	**Fuselage**				**Honeycomb**	**Porous Material**			
Sample	**a**	**b**	**c**	**d**	**Panel**	**Fiber 0.6**	**Fiber 1.2**	**Melam. 0.3**	**Melam. 0.6**
1	X								
2		X							
3			X						
4				X					
5					X				
6	X					X			
7	X						X		
8	X							X	
9	X								X
10				X					X
11					X	X			

Table 2. Inverse characterization parameters of the porous material used in this study.

	ρ **[kg/m^3]**	σ **[Rayls/m]**	ϕ	α	Λ **[μm]**	Λ' **[μm]**
Fiberglass 0.6 pcf	9.6	30808	0.95	1	67.9	430
Fiberglass 1.2 pcf	19.2	109264	0.99	1	35.8	77.2
Melamine 0.6 pcf	9.6	17605	0.95	1	146	216
Melamine 0.3 pcf	4.8	13363	0.99	1	77.1	119

inform that the expression "radiation efficiency" is theoretically presented as a characteristic of the structure under free vibration and of the environment where it is in, i.e., it does not depend on the excitation. However, in this study this same expression will be used on cases with forced excitation, being analyzed for the two different types of excitation on the panels (Davy (2009)). Concerning the conclusions made, the differences presented throughout the text are based on visual observation of the measured and calculated curves, and they can be related to the global levels of the results.

The first comparison made is between configurations 1 (baseline panel) and 5 (honeycomb panel), presented in Fig. 3, considering the two excitations previously presented using filled and dotted lines for DAF and shaker, respectively. This same format will be used in all following figures. As it can be seen in this figure, for the mean-quadratic speed spectrum and the generated sound power level using shaker excitation, there is a peak on 3k Hz, which comes from a shaker and fixed structure set resonance and, consequently, causes an increase in the input power. In general, the measured mean-quadratic speed for the shaker excitation is higher than the one measured for the DAF excitation, which generates a higher level of sound power in frequencies nearby 1k Hz. Therefore, the radiation efficiency of the panel when excited by the DAF is higher in this frequency range.

Figure. 3 also presents that, for the shaker excitation, the difference between the radiation efficiencies for both excitations is higher for the baseline panel than it is for the honeycomb panel. This result comes from the fact that the honeycomb panel has a lower critical frequency, causing a more resonant behavior. This allows the shaker to excite it with a higher radiation efficiency and reach a difference from the baseline panel of 10 dB. It is also important to highlight that the radiation efficiency of the honeycomb panel for the DAF excitation is 5 dB higher than the baseline panel for the same excitation. Thus, even the honeycomb panel has a ratio τ_∞/τ_r smaller than the baseline panel, configuration 5 has both τ_∞ and τ_r higher than configuration 1. This initial comparison highlights the high radiation efficiency of the honeycomb panel, a behavior that is undesired from the cabin noise control perspective.

The baseline fuselage panel (configuration 1) and its variations assessed: thick skin (configuration 2), three frames (configuration 3), and chemical machining, are compared in Fig. 4. As presented, when configuration 2 is loaded with a shaker, it has a higher radiation efficiency and, consequently, higher radiated sound power than configuration 4. However, when the DAF excitation is applied, configuration 4 has higher responses than configuration 2. Even though the radiation efficiency for configuration 4 is not higher than for configuration 2 considering this setup - they are closer when compared with those from shaker excitation -, the Sound Power Level (SWL) of configuration 4 exceeds the last one because of its higher vibrational response. This behavior is coherent with the ratio τ_∞/τ_r. Regarding configurations 1 and 3, they follow the intermediate behavior between both previous configurations.

Comparing the honeycomb panel (configuration 5) and the configuration with the honeycomb panel and the 3 inches of fiberglass 0.6 pcf (configuration 11), it can be seen in Fig. 5 on the mean quadratic velocity result with structural excitation, that adding the porous material causes an increase of the damping on the panel below its critical frequency. It is already known that when the porous material is positioned on the emitting reverberation room side, it increases

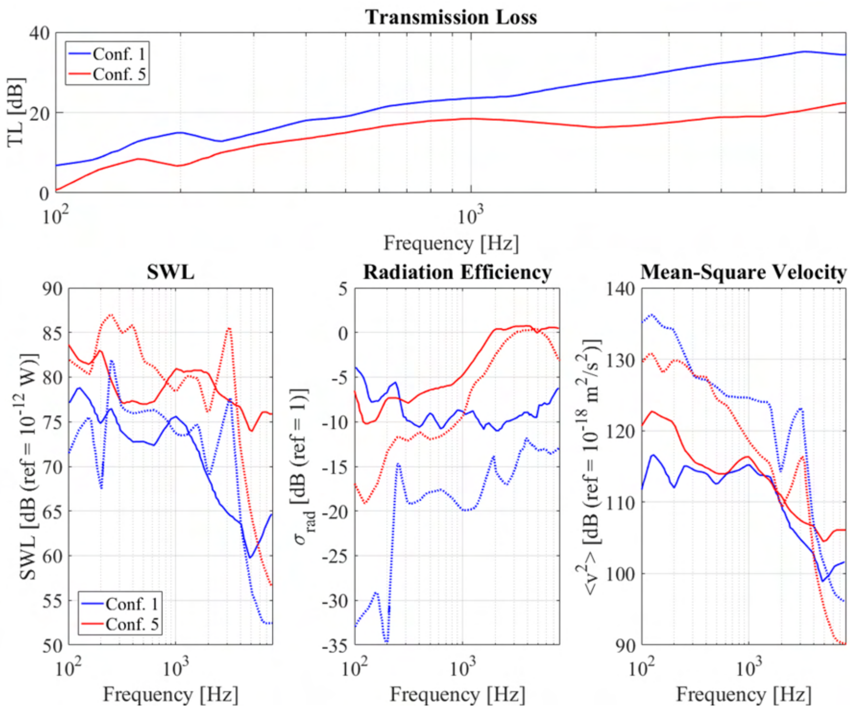


Figure 3. Comparison of configurations 1 and 5, considering DAF and shaker excitations.

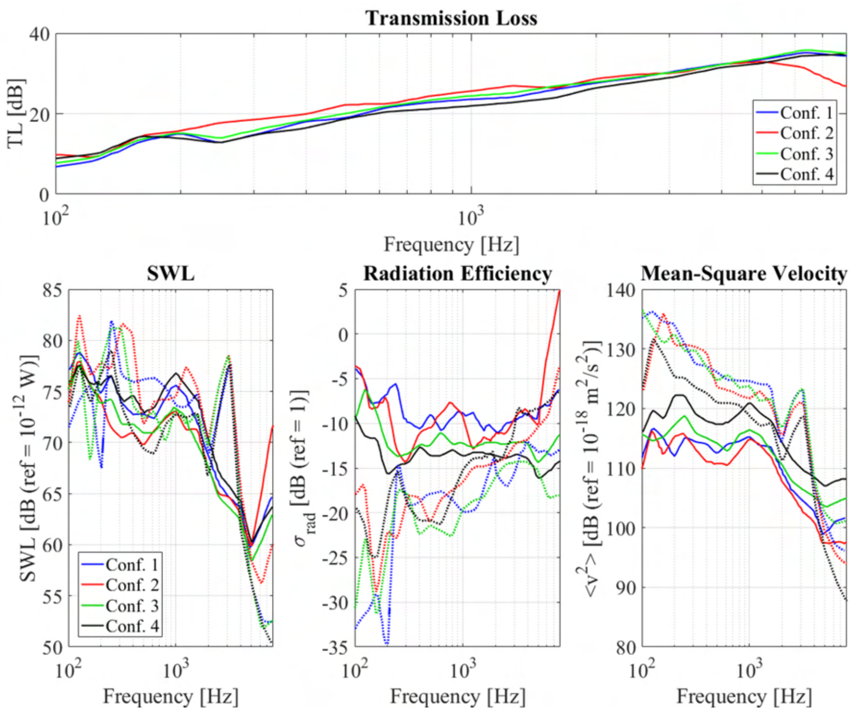


Figure 4. Comparison of configurations 1 to 4, considering DAF and shaker excitations.

the acoustic absorption of the cavity as the frequency also increases, producing a decreasing behavior on the radiation acoustic power for both excitations. However, the radiation efficiency of the panel with porous material overcomes the panel without the porous material until the frequency band of 2000 Hz. This result is due to the addition of the damping, which increases τ_∞/τ_r and consequently the radiation efficiency. Moreover, both the radiated power and the vibration level decrease due to the same phenomenon.

Figure 6 compares the results found using panels with a 3-inches layer of a porous material: fiberglass 0.6 pcf (configuration 6), fiberglass 1.2 pcf (configuration 7), melamine 0.3 pcf (configuration 8) and melamine 0.6 pcf (configuration 9). Figure 6 also present that fiberglass 1.2 pcf, the porous material with the highest resistivity flow, is the most effective

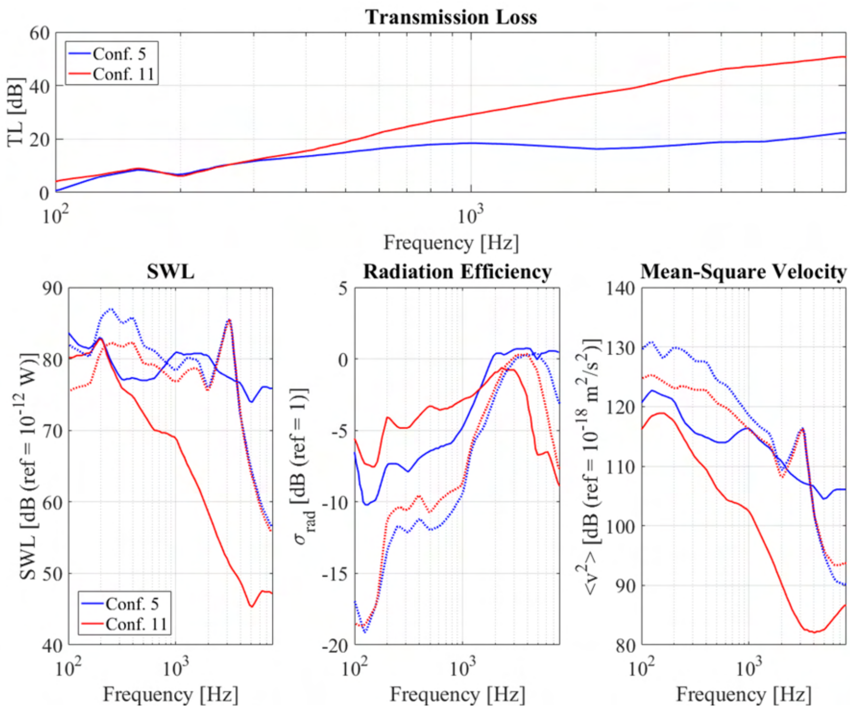


Figure 5. Comparison of configurations 5 and 11, considering DAF and shaker excitations.

material for the reduction of the quadratic velocity of the panel and the radiated SWL, even though its radiation efficiency on the lower frequencies is higher for the previous reason. The mean-squared velocity and the SWL of the panel with melamine (configurations 8 and 9) over DAF appears to maintain higher values than fiberglass due to its lower flow resistivity and more rigid structure, which allows greater sound propagation due to its structural phase. Considering that the shaker is directly coupled to the panel, the porous material in these configurations only works to add damping to the panel, with a consequent increase in radiation efficiency. In the DAF case, however, it is observed that the porous material mischaracterizes the acoustic field that excites the panel, strongly deteriorating its radiation efficiency with increasing frequency.

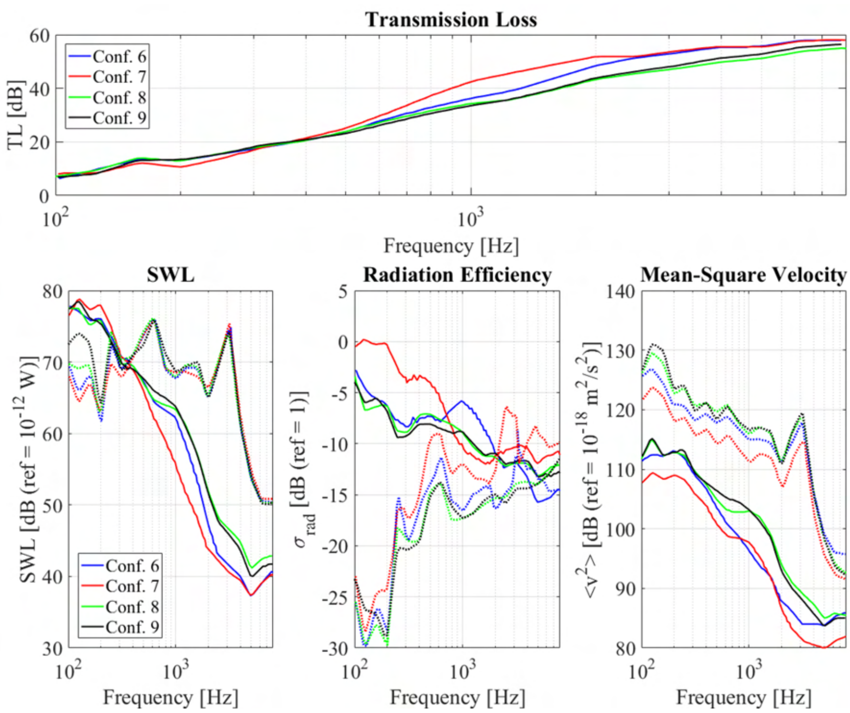


Figure 6. Comparison of configurations 6 to 9, considering DAF and shaker excitations.

Configuration 10 is presented in Fig. 7, composed by a panel with chemical machining and melamine 0.6 pcf. This panel has a higher ratio τ_∞/τ_r, causing the vibration generated by the shaker to offer lower radiation efficiency compared to configuration 9, resulting in lower SWL. As for the DAF case, configuration 10, as it is lighter, results in higher SWL, with radiation efficiency similar to configuration 9, except at high frequencies due to the approach of the critical panel frequency of configuration 9.

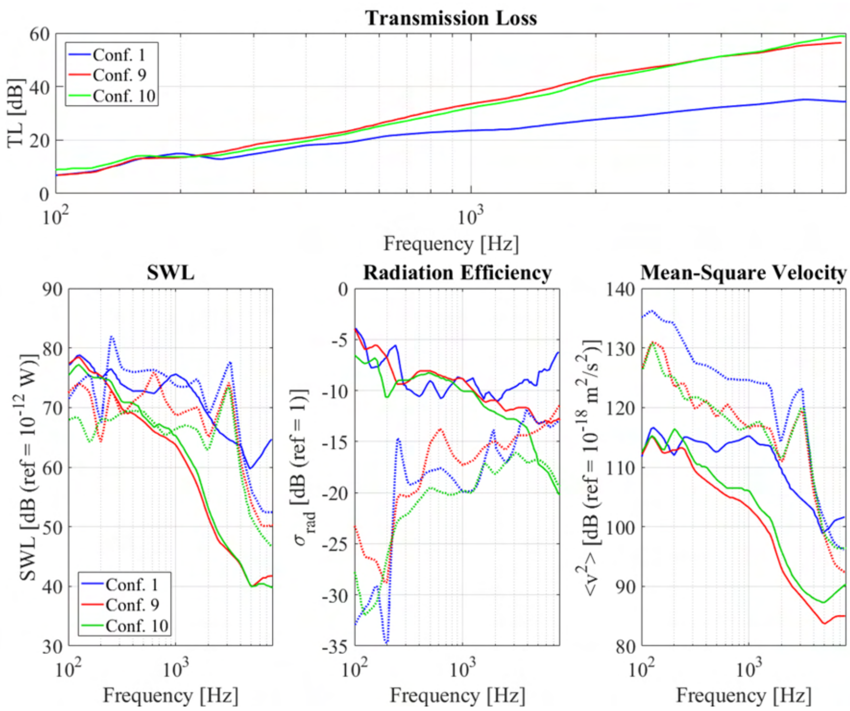


Figure 7. Comparison of configurations 1, 9, and 10, considering DAF and shaker excitations.

4. CONCLUSION

This study presented the measurement results of 11 different configurations of single fuselage panels, using two different kinds of excitation: a punctual force and a diffuse acoustic field. Through different comparisons between results, the relation of excitation, the setup configurations, and the structural and acoustical parameters were analyzed, reaching the results presented in this study.

It is important to highlight that reducing the vibration and the radiated power does not imply the decrease of the radiation efficiency. In many cases, applying the noise control treatment provokes an increase the radiation efficiency. Besides, regarding the honeycomb panel, its radiation efficiency is high, which puts this kind of structure at the top of the list of elements that deserve more attention in vibroacoustic design. For instance, the added damping from the porous material is not expanded for a large range of the assessed frequency on the honeycomb panel when compared to fuselage panels, since the former has a lower critical frequency. Therefore, the viscoelastic material applied to the interior panel seems to be a good choice for this noise control treatment. Moreover, results also showed that the excitation must be evaluated along with the structural configuration for a noise control project, which means that, ideally, a partition should be designed according to the characteristics of the excitation to which it must be submitted.

5. ACKNOWLEDGEMENTS

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