Acoustic study of sandwich panels for use in aeronautic applications: Computational Model

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Abstract

The present study investigates the effect of sandwich panels in sound absorption. Composite materials (carbon fiber and glass fiber) and foams (Airex C70.75) are analyzed in different layup distributions. The main objective of this study is to identify which panel design is better in sound absorption, for low frequency values. These panels are studied in order to optimize a UAV structure (Portuguese Air Force) and support the experimental thesis. This topic is of particular importance, given the growing interest in sandwich panels for the construction of aircraft structures. This work was performed using FEM simulations in the commercial program Ansys. In order to predict the behavior of the panels, three different setups were used: acoustic cavity (ideal), suspended panel surrounded by fluid (simulating experimental conditions) and reverberation-anechoic chamber system (simulating experimental conditions), where transmission loss plots were obtained. Results show that panels composed by a combination of carbon fiber, applied on outside layers, and glass fiber, applied in inside layers generate lower noise levels for low frequencies.

Keywords: Sandwich panels, Transmission Loss vs frequency, harmonic response, Carbon fiber panels, Glass fiber panels

1. Introduction

In the aeronautical industry, the most important parameter is weight, especially in UAV designs. It is noteworthy that all of the almost 200 UAV models [1] include some composite part: Glass and quartz fiber are used in sensors and nose cones but carbon fiber is the primary material used in structures due to the demand for payload capacity. These UAVs can be divided into four different categories: target drones, Radar decoy, ISR (information, surveillance and reconnaissance) aircraft and combat aerial vehicles (UCAVs).

In 2007, UAVs where in service in more than 50 countries and logged more than 500.000 flight hours, this value is expected to grow at a logarithmic rate. Also it is know that thousands of different UAV designs are in various stages of development, the UAV market is expected to account for $55Billion (USD) by 2018[1].

With the shift towards composite materials and unmanned aircraft vehicles, there is a need for better understanding of the acoustic behaviors associated with these types of materials. Early theoretical models were developed for isotropic foams by Kurtze and Watters [2] and Ford [3]. Kurtze and Watters investigated the propagation speed of both flexural and shear waves in order to obtain the total impedance of sandwich panels. This model is extremely important, to prove that coincidence frequencies can be moved to outside the range of interest by using cores with variable shear speeds. Ford [3] studied the effect of natural frequencies on the transmission loss of the sandwich panel using an energy formulation and concluded that core thickness and Poisson ratio significantly influence the natural frequencies of symmetrical modes.

However the theoretical models lack when sandwich panels start to become more complex. This coupled with the development in computational power, has unbalanced the scales from theoretical models to numerical models. Numerical models can be divided into two approaches: finite and boundary elements models and Statistical Energy Analyses.

Finite and boundary elements should only be used for low frequency values, due to the fact that fluid element size is proportional to the wavelength size [4]. Assaf and Guerich [5] proposed a model separating structural domain and fluid domain by adding an element-boundary element, which was experimentally validated for low frequencies [6]. Kim and Han [7] introduced the HAFEM a hybrid analytical/finite element method. This model is based in a finite element approximation in the thickness direction, which creates a necessity for the layers to have constant thickness and to be homogenous. This method can be accurate with one finite element per layer.

Statistical Energy Analyses is an energy based method developed by Lyon [8] that can be applied for high frequency applications. The fundamental equation is obtained from the power balance of three different systems.

In this work FEM models are being used to investigate the effect of sandwich panels, which are applied inside a UAV structure, for sound absorption. The results from multiple panels are compared, in order to choose the best panel design for our application.

2. Materials, panel dimensions and orientations

The materials used in this work are: carbon fiber, glass fiber, Airex C70.75 and structural steel. These material properties are obtained from experimental work and datasheets [9] seen in table 1. It is important to note that structural steel is only going to be used in the computational simulations and in the introduction to the setups.

Structural Steel	
ρ	7.85 g/cm^3
E	200000 MPa
v	0.3

Airex C70.75	
ρ	80 kg/m^3
E	63 MPa
G	30 MPa

Panel dimensions	
Length	300mm
Width	200mm
Orientations	0º and 90º

	Carbon Fiber	Glass Fiber
ρ	1.5 g/cm^3	2.5 g/cm^3
E_1	78594 MPa	44603 MPa
E_2	11441 MPa	12626 MPa
E_3	11441 MPa	12626 MPa
v_{12}	0.2079	0.34917
v_{13}	0.2079	0.34917
v_{23}	0.2079	0.34917
G_{12}	3502.1 MPa	5532.3 MPa
G_{23}	2927.6 MPa	4823.2 MPa
G_{13}	4083.1 MPa	5210.6 MPa

Table 1 Material properties and panel dimension

The panel dimensions chosen were 300mm x 200mm that resemble the final panel design and the fiber orientations 0º and 90º, take into consideration the hand layup technique limitations.

3. Natural Frequencies and Mode Shapes

Before beginning the harmonic response analyses, multiple modal studies need to be performed in order to identify structural modes and acoustic modes

In figure 1 and table 2, the structural frequencies and modes shapes for a structural steel panel with 3mm thicknesses is shown. The panel is modeled with 25mm SOLID186 elements and has clamped boundary conditions.

Mode	Clamped (solid)
1	491.8Hz
2	758.83Hz
3	1201.8Hz
4	1209Hz
5	1449.2Hz
6	1829.4Hz
7	1870.5Hz
8	2270.9Hz

Table 2 Structural Steel panel Clamped frequencies

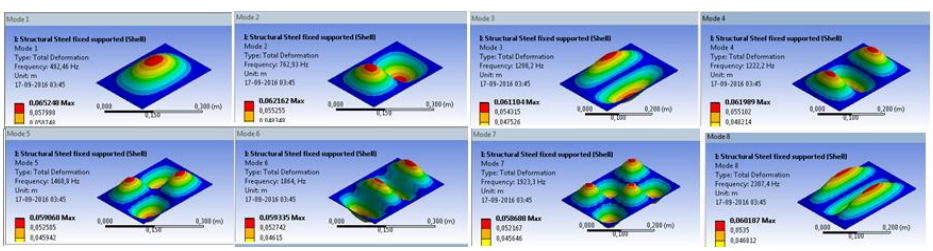

Figure 1 Structural Steel Clamped mode shapes

In figure 2 and table 3, the acoustic frequencies and mode shapes for an acoustic cavity with 300mmx200mmx200mm is shown. The acoustic cavity is modeled with 25mm FLUID220 elements and is constrained by reflective rigid walls.

Mode	Acoustic Cavity
1	572,07Hz
2	858,11Hz
3	858,11Hz
4	1031,3Hz
5	1031,3Hz
6	1144,2Hz
7	1213,5Hz
8	1341,6Hz

Table 3 Acoustic Cavity frequencies

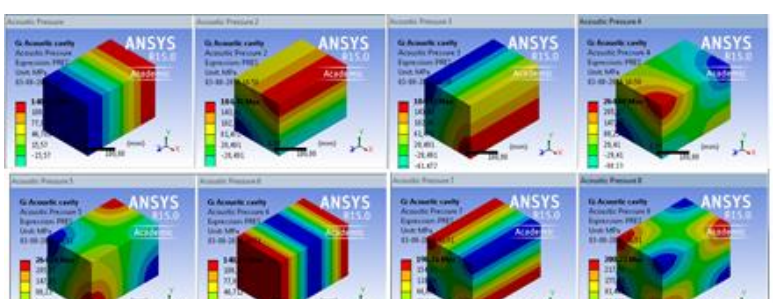

Figure 2 Acoustic Cavity mode shapes

4. Acoustic cavity with mechanical excitation and sound pressure excitation setups

The model acoustic cavity with mechanical excitation (single cavity model) is shown in figure 3, where the panel is shown in red and the acoustic cavity in gray. The panel is a 3mm structural steel discretized with 25mm SOLID186 elements and clamped boundary conditions. The acoustic cavity has 300mmx200mmx200mm, is discretized by 25mm FLUID220 elements and is surrounded by 5 rigid reflective walls and the panel [10].

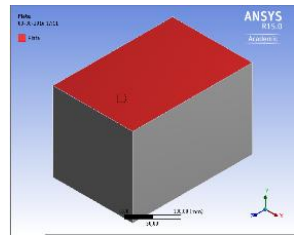

Figure 3 Single Cavity model geometry

The model acoustic cavity with sound pressure excitation (two cavity model) is shown in figure 4, where the panel is placed between the two acoustic cavities. The panel is same one used in the single cavity models. Both acoustic cavities have dimensions 300mmx200mmx200mm, are discretized with 25mm FLUID220 elements and the following boundary conditions: top cavity is modeled as a duct (top face is radiant) and the bottom cavity is surrounded by reflective walls [10].

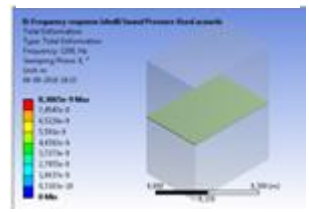

Figure 4 Two cavity model geometry

5. Natural frequencies and mode shapes for the single cavity and two cavity setups

In table 4, figure 5 and 6, the natural frequencies and mode shapes are shown. These values are obtained from modal studies for the system model using Fluid-Structure interface.

Mode	Panel	Acoustic Cavity	Single cavity model	Two cavity model
1	492,46Hz	572,07Hz	492.01Hz	491.6Hz
2	762,93Hz	858,11Hz	571.72Hz	571.37Hz
3	1208,2Hz	858,11Hz	762.3Hz	572.07Hz
4	1222,2Hz	1031,3Hz	857.93Hz	761.71Hz
5	1468,8Hz	1031,3Hz	858.68Hz	857.73Hz
6	1864Hz	1144,2Hz	1031.2Hz	858.12Hz
7	1923,3Hz	1213,5Hz	1031.9Hz	858.12Hz
8	2307,4Hz	1341,6Hz	1143.7Hz	859.23Hz

Table 4 Natural frequency for the panel, acoustic cavity, single cavity model and two cavity model

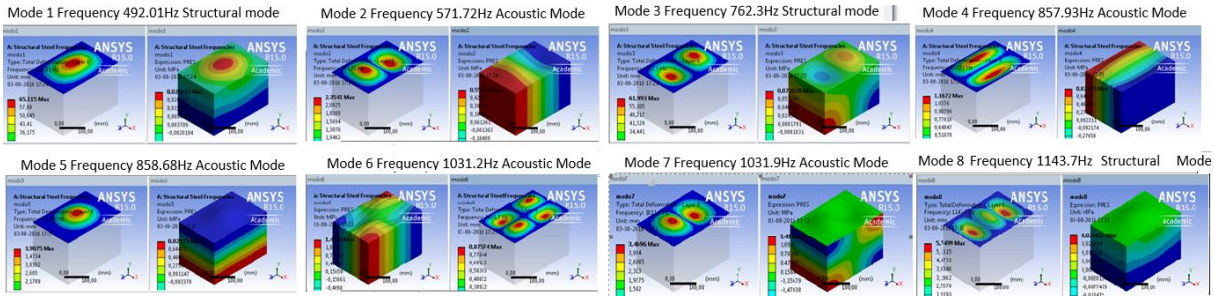

Figure 6 Structural and Acoustic mode shapes for the single cavity system

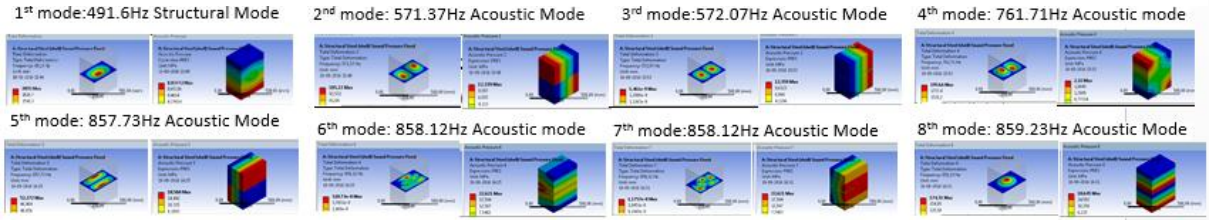

Figure 5 Structural and Acoustic Mode shapes for the two cavity model

6. SPL frequency plots

In figure 7, the SPL vs frequency plot for the single cavity and two cavity model using a 3mm structural panel are shown. These plots were obtained from an excitation of 1Pa (top of the panel) and 1.2099m/s (top face of acoustic cavity) for single cavity and two cavity model. The 1.2099m/s velocity was applied on the top face in order to obtain a uniform pressure distribution that recreates a 1Pa pressure on top of the panel.

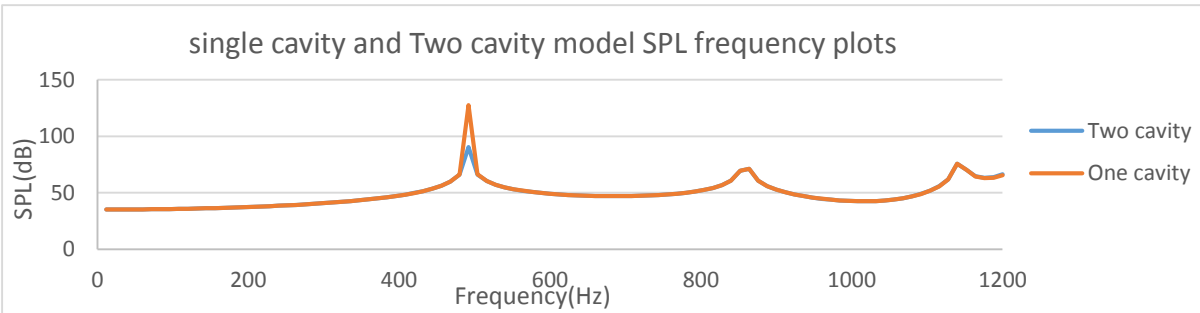

Figure 7 SPL vs frequency plot for single cavity system and two cavity system

Analyzing the plots, three different critical points can be identified: 492Hz, 864Hz and 1152Hz. The total panel deformation and pressure distributions obtained from the harmonic analyses are shown in figure 8.

- The 492Hz mode is a structural mode that corresponds to the first structural mode 492.46Hz from the single cavity modal study.
- The 864Hz mode is an acoustic mode, that mode corresponds to the 5th mode of the single cavity model and the 3rd acoustic mode 858.68Hz.
- The 1152Hz mode is an acoustic mode that doesn't appear in the single cavity model, but this acoustic mode corresponds to the 6th mode 1144.2Hz obtained in the acoustic cavity model.

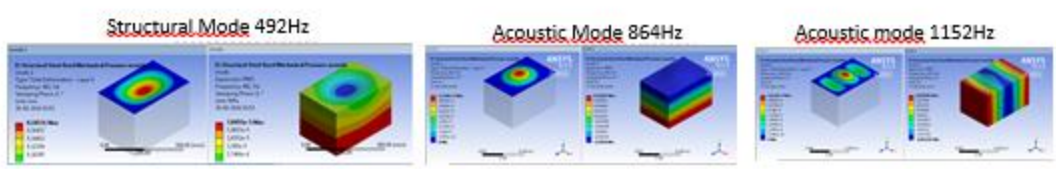

Figure 8 Modes detected in the SPL frequency plot

Also from figure 7, we can see that both two cavity and single cavity models give similar SPL frequency results. Taking this into account, only the single cavity model is going to be used in panel comparison in order to save computational power and simulation time.

7. Experimental Setups

As this work was performed in order to support an experimental thesis, experimental setups were simulated.

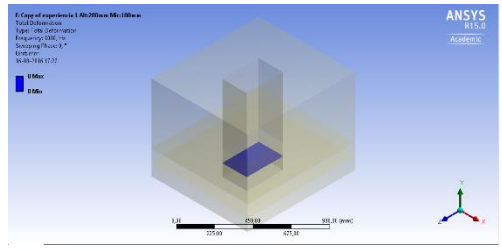

Figure 9 Setup 1 model

Setup 1 model is shown in figure 9, the panel is seen in blue with clamped boundary conditions enclosed by fluid. The boundary conditions in the fluid are defined in order to recreate an infinite fluid domain [10].

The excitation is created by bare loudspeaker [10] placed 200mm above the panel. In order to calculate the transmission loss on the panel two different microphones are placed 100mm above and below the panel.

$$TL = 20\log_{10}\left(\frac{P_{ext}}{P_{in}}\right) \qquad (1)$$

Where P_{ext} and P_{in} are the pressure measured after and before the panel.

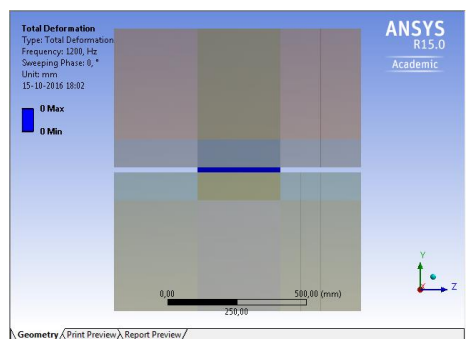

Figure 10 Setup 2 model

Setup 2 is shown in figure 10. This setup is the most common built experimental setup, used for acoustic studies, where an anechoic chamber (top chamber) and a reverberation chamber (bottom chamber) are built.

The reverberation chamber has the following parameters: Rectangular prism (900mm x 800mm x 500mm), constrained with rigid reflective walls, and is where the bare loudspeaker is applied. The anechoic chamber has the same dimensions however instead of reflective walls the walls constraining this chamber are has fully absorbing walls (α=0). These two chambers are only connected by the faces of the panel in study. This means that the extra area surrounding the panel between the chambers is modeled as a rigid wall.

In order to calculate the Transmission Loss a similar procedure from setup 1 is applied: one microphone is placed 100mm above the panel and other 100mm below the panel. The Transmission loss is obtained from equation 2.

$$TL = 20\log_{10}\left(\frac{P_{rev}}{P_{ane}}\right) \qquad (2)$$

Where P_{rev} is the pressure measured by the microphone located in the reverberation chamber and P_{ane} is the pressure measured in the anechoic chamber.

8. TL frequency plots for experimental setup

In figure 11, an example of both experimental setups TL frequency plots for a bare loudspeaker excitation (1Pa and radius=50mm) are shown for the sandwich panel represented in table 5 and 6

	Sandwich panel
Number of layers	9
Total Thickness	7mm
Weight	0,2124 kg
Layup materials	CF/CF/CF/CF Airex C70.75 CF/CF/CF/CF
Layup orientation	[[0/90/90/0] [Foam] [0/90/90/0]
Carbon Fiber layer thickness	0.25mm
Foam thickness	5mm

Table 5 Sandwich panel layers, materials and orientations

Modo	**Frequencies(Hz) Clamped**
1	685.9Hz
2	962.18Hz
3	1249.1Hz
4	1360.2Hz
5	1431.1Hz
6	1731.1Hz

Table 6 Natural frequencies of the sandwich panel in Clamped conditions

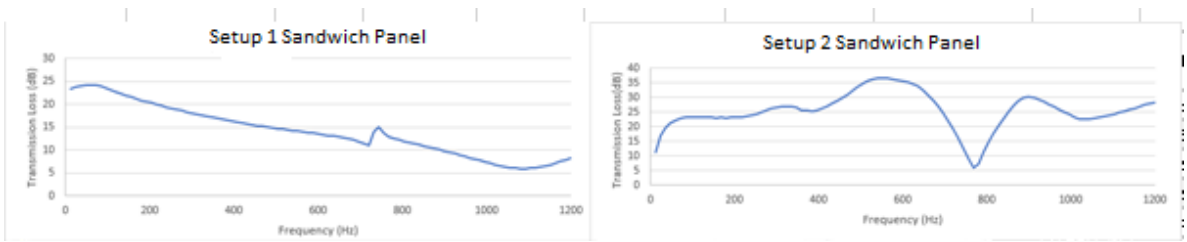

Figure 11 Setup 1 and Setup 2 TL frequency plots

From setup 1 two behaviors are going to be investigated: the increase in the TL at 756Hz and the valley that occurs in the 1000Hz to 1200Hz frequency range. The pressure distribution below the panel for an excitation frequency of 756Hz can be seen in figure 12. It can be seen that the pressure depends clearly on the panel deformation, which is similar to a structural mode. However, for other frequency values the behavior is influenced by the fluid on the upper

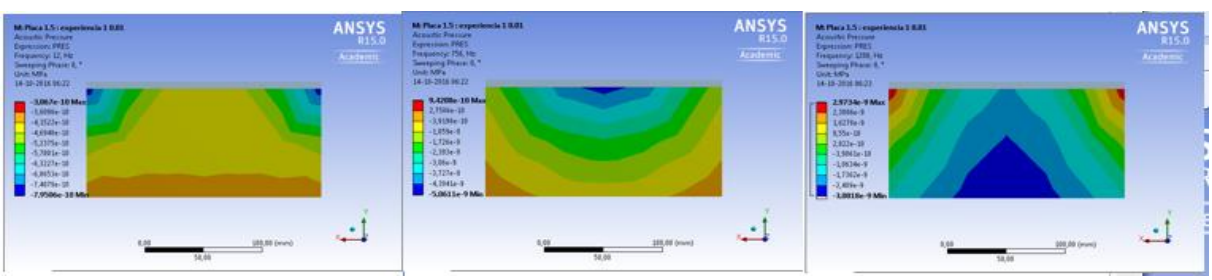

Figure 12 Setup 1 pressure distribution below the panel for 12Hz, 756Hz and 1200Hz

face of the panel. Regarding the valley that seen between 1000Hz and 1200Hz, it occurs because of the coincidence frequency (1080Hz), this frequency occurs when both acoustic and flexural vibration wave-lengths coincide [11]. In equation 3 this coincidence frequency is calculated for infinite panels and is proportional to the thickness [12], but since we are working with thin panels this coincidence frequency values is going to remain almost constant.

$$f = \frac{c^2}{2\pi}\sqrt{\frac{m_f + 0.5m_c}{D_f}} \quad (3)$$

From setup 2, only one particular behavior is going to be analyzed, at frequency point 768Hz. The pressure distribution is seen in figure 13, on the acoustic body after the panel. This point is analyzed because it creates the lowest transmission loss in the frequency range. Also comparing both experimental setups, we can see that the pressure distribution is similar for both models and the values are similar: 756Hz and 768Hz.

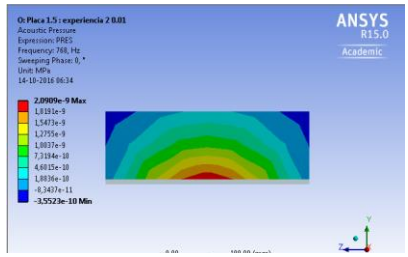

Figure 13 Setup 2 pressure distribution at 768Hz

Taking these values into account, it can be seen that both these points create a pressure distribution similar to the ones seen from structural modes in section 3, although these values do not resemble any of the structural modes obtained from the modal study.

9. Sandwich panels designed

In order to choose the best panel design for our application, eight different groups of panels were simulated using the three models described in this article (single cavity model, setup 1 and setup 2) for two different constant damping factors of ξ=0.01 and ξ=0.1:

- Panel group 1: carbon fiber sandwich panels with variable foam thicknesses of 0mm, 3mm, 5mm and 7mm described by the following layup [4 carbon fiber layers/ Airex C70.75 / 4 carbon fiber layers], layer orientations [0/90/90/0/0/0/90/90/0].
- Panel group 2: glass fiber sandwich panels with variable foam thicknesses of 0mm, 3mm, 5mm and 7mm described by the following layup [4 glass fiber layers/ Airex C70.75 / 4 glass fiber layers], layer orientations [0/90/90/0/0/0/90/90/0].
- Panel group 3: combination of carbon fiber and glass fiber sandwich panels with variable foam thicknesses of 3mm, 5mm and 7 mm described by the following layup [2 glass fiber layers/4 carbon fiber layer/Airex C70.75 /4 carbon fiber layer / 2 glass fiber layers], layer orientations [0/90/0/90/90/0/0/0/90/90/0/90/0].
- Panel group 4: combination of carbon fiber and glass fiber sandwich panels with variable foam thicknesses of 3mm, 5mm and 7 mm described by the following layup [4 carbon fiber layers/2 glass fiber layer/Airex C70.75 /2 glass fiber layer /4 carbon fiber layers], layer orientations [0/90/90/0/0/90/0/90/0/0/90/90/0/90/0].
- Panel group 5: combination of carbon fiber and glass fiber sandwich panels with double foam, variable foam thicknesses of 1.5mm, 3mm and 4.5 mm described by the following layup [4 carbon fiber layers/Airex C70.75/ 4 glass fiber layer / Airex C70.75 / 4 carbon fiber layers], layer orientations [0/90/90/0/0/0/90/90/0/0/0/90/90/0].

- Panel group 6: carbon fiber sandwich panels with double foam, variable foam thicknesses of 1.5mm, 3mm and 4.5 mm described by the following layup [4 carbon fiber layers/Airex C70.75/ 4 carbon fiber layer / Airex C70.75 / 4 carbon fiber layers], layer orientations [0/90/90/0/0/0/90/90/0/0/0/90/90/0].
- Panel group7: combination of carbon fiber and glass fiber sandwich panels with double foam, variable foam thicknesses of 1.5mm, 3mm and 4.5 mm described by the following layup [4 glass fiber layers/Airex C70.75/ 4 carbon fiber layer / Airex C70.75 / 4 glass fiber layers], layer orientations [0/90/90/0/0/0/90/90/0/0/0/90/90/0].
- Panel group 8: glass fiber sandwich panels with double foam, variable foam thicknesses of 1.5mm, 3mm and 4.5 mm described by the following layup [4 glass fiber layers/Airex C70.75/ 4 glass fiber layer / Airex C70.75 / 4 glass fiber layers], layer orientations [0/90/90/0/0/0/90/90/0/0/0/90/90/0].

These panels are being named according to its layup: CF-carbon fiber, GF-glass fiber and other values are foam thicknesses, for example CF/3/GF/3/CF is a panel with a carbon fiber/Airex C70.75/Glass Fiber/Airex C70.75/Carbon fiber.

The Transmission frequency plots were obtained for the three models. Results for panel group 3, 4 and 5 are illustrated in figure 14.

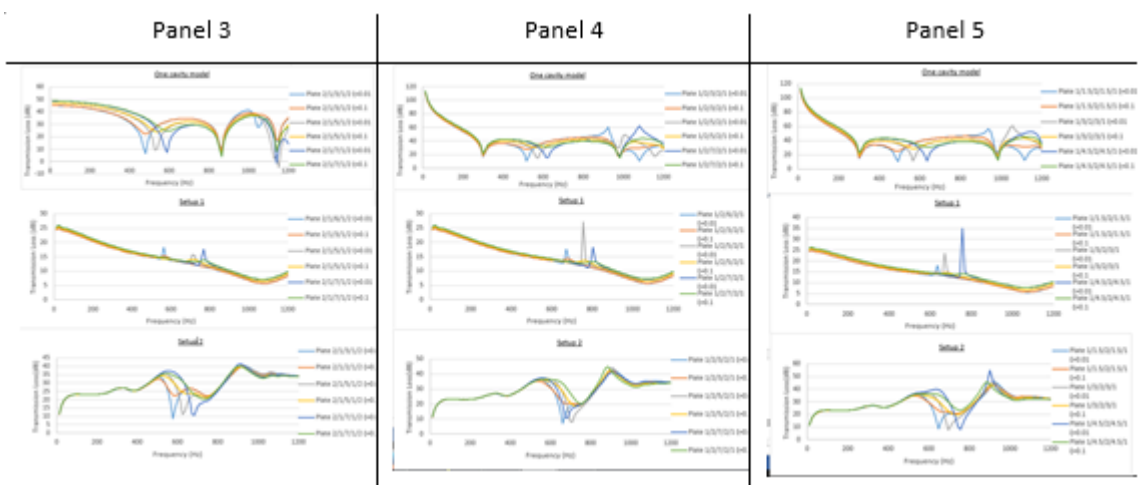

Figure 14 TL frequency plot for panel groups 3, 4 and 5

10. Panel Comparison

Taking into account our sandwich panel application two parameters are going to be used to choose the best panel design: transmission loss for low frequencies and first structural modes. Table 7 shows these values in terms of transmission loss for all panels studied in the single cavity model (ideal) and a constant damping factor of ξ=0.01:

Analyzing the Transmission loss for low frequency, panel groups 4 and 5 have the best behavior in term of sound absorption (values shown in green). Also from panel CF/GF/3/GF/CF and panel CF/1.5/GF/1.5/GF/CF, which have the same amount of carbon fiber, glass fiber and foam, with the only difference being one foam core or two foam core, the 1st structural point occurs at 516Hz and 492Hz.

With this in mind, we can conclude that group 4 panels have the best acoustic behavior, per unit of foam thickness, to be applied in the UAV structure, due to the high transmission loss for low frequency and a relatively high structural mode frequency.

		1st Critical Point		TL(Low Frequency)			
		CDC : 0.01					
		1st CP	TL(CP)	12Hz	150Hz	300Hz	450Hz
Group 1	Panel CF/0/CF	300Hz	-1.79dB	29,86dB	26.94dB	-1.79dB	29.19dB
	Panel CF/3/CF	564Hz	-2.57dB	40,33dB	39.31dB	35.86dB	27.80dB
	Panel CF/5/CF	672Hz	-0.97dB	43,61dB	42.77dB	40.06dB	34.58dB
	Panel CF/7/CF	756Hz	-5.37dB	45,96dB	45.21dB	42.82dB	38.22dB
Group 2	Panel GF / 0 / GF	384Hz	8,96dB	44,67dB	42,90dB	35,24dB	31,67dB
	Panel GF / 3 / GF	456Hz	6,54dB	46,49dB	46,48dB	39,94dB	11,18dB
	Panel GF / 5 / GF	504Hz	7,23dB	48,32dB	48,31dB	42,95dB	30,82dB
	Panel GF / 7 / GF	552Hz	7,10dB	49,85dB	49,84dB	45,17dB	36,42dB
Group 3	Panel GF / CF / 3 / CF / GF	480Hz	6.34dB	45,14dB	43,85dB	39,15dB	21,79dB
	Panel GF / CF / 5 / CF / GF	540Hz	7.66dB	47,10dB	46,00dB	42,16dB	32,36dB
	Panel GF / CF / 7 / CF / GF	588Hz	7.66dB	48,71dB	47,72dB	44,38dB	36,88dB
Group 4	Panel CF / GF / 3 / GF / CF	516Hz	10.49dB	110,14dB	62,70dB	16,97dB	33,66dB
	Panel CF / GF / 5 / GF / CF	576Hz	14.74dB	111,60dB	64.43dB	19,59dB	38,77dB
	Panel CF / GF / 7 / GF / CF	624Hz	15.95dB	113,13dB	65.92dB	21,79dB	41,91dB
Group 5	Panel CF / 1,5 / GF / 1,5 / CF	492Hz	10.34dB	109,14dB	61,62dB	15,36dB	28,35dB
	Panel CF / 3 / GF / 3 / CF	564Hz	11.58dB	111,63dB	64.40dB	19,68dB	38,51dB
	Panel CF / 4,5 / GF / 4,5 / CF	636Hz	11.66dB	113,74dB	66.54dB	22,83dB	42,97dB
Group 6	Panel CF / 1,5 / CF / 1,5 / CF	516Hz	3.90dB	41,44dB	40,27dB	36,13dB	24,45dB
	Panel CF / 3 / CF / 3 / CF	624Hz	0.72dB	45,24dB	44,32dB	41,31dB	34,95dB
	Panel CF / 4,5 / CF / 4,5 / CF	720Hz	-2.50dB	47,90dB	47,11dB	44,55dB	39,52dB
Group 7	Panel GF / 1,5 / CF / 1,5 / GF	444Hz	4.04dB	46,82dB	45,38dB	39,91dB	11,18dB
	Panel GF / 3 / CF / 3 / GF	504Hz	7.10dB	49,10dB	47,91dB	43,70dB	31,48dB
	Panel GF / 4,5 / CF / 4,5 / GF	564Hz	9.74dB	50,96dB	49,92dB	46,38dB	37,99dB
Group 8	Panel GF / 1,5 / GF / 1,5 / GF	456Hz	10.17dB	49,73dB	48,36dB	43,28dB	16,21dB
	Panel GF / 3 / GF / 3 / GF	504Hz	9.77dB	51,30dB	50,10dB	45,84dB	33,23dB
	Panel GF / 4,5 / GF / 4,5 / GF	540Hz	14.10dB	52,76dB	51,69dB	47,98dB	38,85dB

Table 7 First critical point and TL at low frequency values for all panels studied

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