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## PARAMETRIC ANALYSIS OF A TRIPLE CORE PERIODIC UNIT CELL INCLUDING A MIDDLE RANDOM CORE – SMART 2019

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**Keywords:** multi-layer core, sandwich panels, transmission loss, periodic structures.

**Abstract.** In the last decades, the main issue concerning structures is related to weight constraint. Many solutions are available as composites or sandwich panels. Nevertheless, it seems that metamaterials such periodic structures focus a specific attention nowadays. In this field, honeycomb structures remain wide used solutions especially in the aerospace industry, but they exhibit a high stiffness-to-weight ratio leading to poor acoustic properties. Consequently, some new designs are created to obtain better acoustic indicators. In this context, this paper proposes to study a new kind of periodic structures using multi-layer core topology systems consisting on stacking layers made of different geometry of cores (auxetic, hexagonal, rectangular...). Several new parameters should be considered to fully understand the dynamic and acoustic behaviour. In this paper we will limit the study to rectangular core combined with a random core located in between. Consequently, we will stack 3 kind of cores: Rect-Random-Rect. The main objective of this study is to analyse the results of the parametric survey. All configurations are constraint to have the same surface density. The chosen acoustic indicator is the Sound Transmission Loss (STL). The transition frequency will be also investigated as well as the compression and shear modulus and the bending waves. Modelling these structures is possible using either Wave Finite Element Method (WFEM) only or combining WFEM and the Transfer Matrix Method (TMM). We assume an infinite panel, real wavenumbers and that the structure is excited by plane waves with the angles of incidence and reflection equal. The model is implemented using MATLAB and ANSYS apdl. Because such structures are made using a 3D printer, the ABS is used as the material for the study. From the parametric study, it turned out that multi-layer core systems correspond to relevant solutions to highly improve the STL. Moreover, it is possible to find out an optimized design giving the best STL. However, as it will be shown, it goes along with less efficiency in terms of mechanical properties and thus should be relevant for some specific applications.

## 1 INTRODUCTION

Lightweight structures including composite panels, sandwich panels or porous media are still widely used in the industry due their low mass. Besides, sandwich panels made of periodic cores exhibit a great interest having a low stiffness to weight ratio but leading to unsatisfactory acoustical properties. Many researches are carried out to provide them better mechanical and acoustical performances according to the industrial application. Proposed designs in the literature begin from simple cases as composite panels, studying the stacking sequences between layers to improve their mechanical efficiency [1,2], up to more complex structures using more exotic shapes and/or adding add-ons [3,4,5,6], especially within the periodic media field. More recently, multi-layer core topology systems have been developed by stacking different layers of cores (auxetic, hexagonal, rectangular, random geometry) to operate with new parameters. A double-layer honeycomb panel has been studied in [7] to drastically reduce the effect of the critical frequency of the Sound Transmission Loss (STL). Besides, corrugated and truss cores are stacked for building applications [8,9,10] trying to reach a more desirable impact resistance. Most of time, authors add damping layers separating the cores. These last designs are mainly considered for their capacity to absorb energy for specific mechanical applications but not employed as concerns acoustics. It is then clearly expected that more complex structures will continue to be investigated in the future to obtain improved properties. Consequently, this paper intends to analyze multi-layer core topology systems within the framework of periodic structures and to perform a parametric survey with the involvement of new parameters. Such approaches have been already completed for vibroacoustic properties in standard cases using honeycomb cores [11,12] or by changing gradually the core from a honeycomb to an auxetic unit cell [13, 14]. They have shown up the influence of geometrical parameters on vibroacoustic indicators (transition frequency, the modal density, the group velocity) and the STL. All these indicators reveal a better comprehension of the phenomenon leading to the improvement of the acoustical performances. In this paper, the parametric survey will be characterized by a study of the geometrical parameters of one layer over three opening new configurations and new perspectives not limited as one-core unit cell structures and leading to a high improvement of the STL.

## 2 MULTI-LAYER CORE TOPOLOGY SYSTEMS

### 2.1 Description

Multi-layer core topology systems are made of several layers of periodic structures (hexagonal, auxetic, rectangular, ...), Fig. 1.

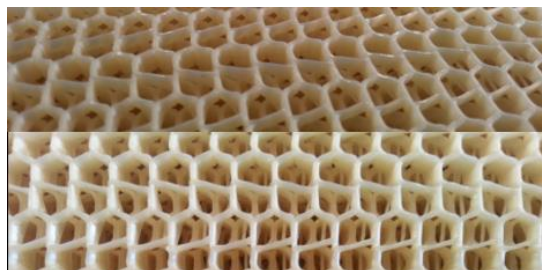


Figure 1 : Multi-layer core topology systems

Such structures involve new parameters to be considered to figure out the dynamic and the acoustic behavior. These parameters are listed as following:

1. The phase shift between layers
2. The rotation between layers
3. The interaction between geometrical parameters of each layer giving the possibility to modify the shape of the unit cell for each layer.
4. The size of the unit cell for each layer.
5. The periodicity of each layer.

The phase shift and the rotation make occur lower rigid contacts between layers leading to new phenomena which tend to affect the transition frequency and decrease the compression modulus of the structure. Nevertheless, their impact on the STL still need to be verified. The phase shift is possible along the direction  $x$  and  $y$ . In addition, the rotation between layers produces a non-periodic structure. The existing methods using the Wave Finite Element Method (WFEM) for the calculation of vibroacoustic indicators are not applicable. Finally, they offer a great added value by keeping the mass constant.

Changing the geometrical parameters for each layer turns out the possibility to have different shape for each layer, and then, combining a hexagonal core with an auxetic or a rectangular core, or more generally random cores and increasing the number of possibilities and the complexity of the unit cell.

Ultimately, the size of the unit cell and the periodicity for each layer are linked. Indeed, the only way to extract a unit cell in this configuration comes out when each layer has a unit cell size multiple to each other and without rotation.

Resulting from these parameters, it is then not always possible to extract the unit cell through the depth of the structure. The entire sandwich panel must be modeled and a high computational is expected. Therefore, some listed parameters will be constrained to have the opportunity to use the WFEM and to apply the model allowing to obtain the STL.

## 2.2 Parametric model

The illustrated parametric model (Fig. 2) will be used for the study. Each layer has the same unit cell size and no rotation is considered. The main purpose in this study is to identify the geometrical influence of the shape of the core. The thickness of the core and the skins as well as the height of each layer will be not altered since it is shown in [4] that they have a strong influence on the mechanical and acoustical properties. Thereby, by keeping the mass constant, only parameters defined in the parametric model influence the STL. An algorithm, developed in the lab, gives the possibility to obtain all configurations having the same surface density for a given size of unit cell. Since the size of the unit cell is maintained and the depth of each layer are equal and the parameter  $n$  is set to  $1/2$ , only 5 parameters are modified:  $a_1$ ,  $a_2$ ,  $a_3$ ,  $\alpha$  and  $\beta$ . However, to represent correctly the result coming from the parametric survey it is necessary to reduce the number of parameters. Consequently, it is decided that  $a_1 = a_2$ .

The size of the unit cell is fixed to  $L_x = 15$  mm and  $L_y = 15$  mm. A sandwich panel with 3 layers is considered. The top and bottom layers correspond to a rectangular core while the middle core is a random core defined by the set of parameters. The depth of each layer is 5 mm. The thickness of the skins and the core is 0,6 mm. The sandwich panel is made of ABS since the 3D

printing technic is commonly used to manufacture these structures, with  $E = 1,8 \times 10^9$  Pa,  $\rho = 985 \text{ kg/m}^3$  and  $\nu = 0,33$ . The damping  $\eta$  is evaluated at 2 %. These values were acquired using a DMA test. From the algorithm, the number of configurations is obtained (Fig. 3) given a certain range of surface density with  $a_3 = L_x/4$ . They will be compared to a standard periodic structure with a rectangular core whose surface density is equal to  $0,57 \text{ kg/m}^2$ . Thereby, 216 configurations are possible. The parameter  $a_3$  is then used to be shifted in the along  $x$  with 6 different values between 0 and  $L_x$ . Consequently, 1296 configurations in total will be computed. For each configuration the STL is calculated. A wise choice for the model must be done to avoid high computational cost.

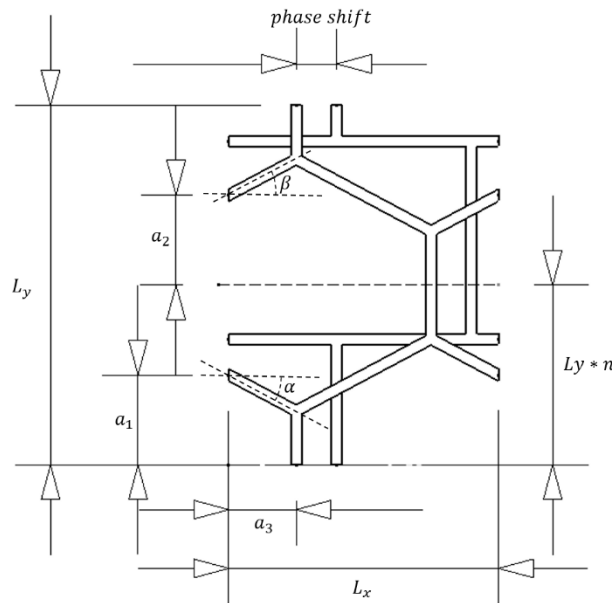


Figure 2 : Parametric model

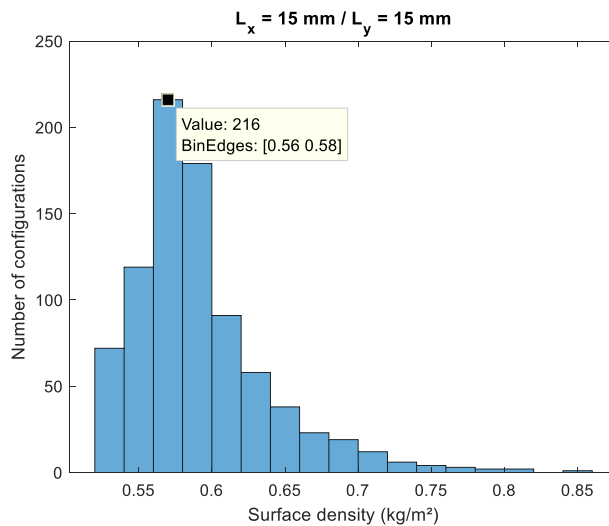


Figure 3 : Number of configurations with  $L_x = 15 \text{ mm}$  and  $L_y = 15 \text{ mm}$  and  $a_3 = L_x/4$ .

By taking this range of surface density and having all the possibilities for each parameter, it is possible to plot each parameter as a function of others. It occurs that the angle  $\alpha$  and  $\beta$  are linked by a logarithmic function as shown in Fig. 4. Consequently, the set of parameters could be reduced to  $a_1$ ,  $a_3$  and  $\alpha$  since  $\alpha = f(\beta)$ .

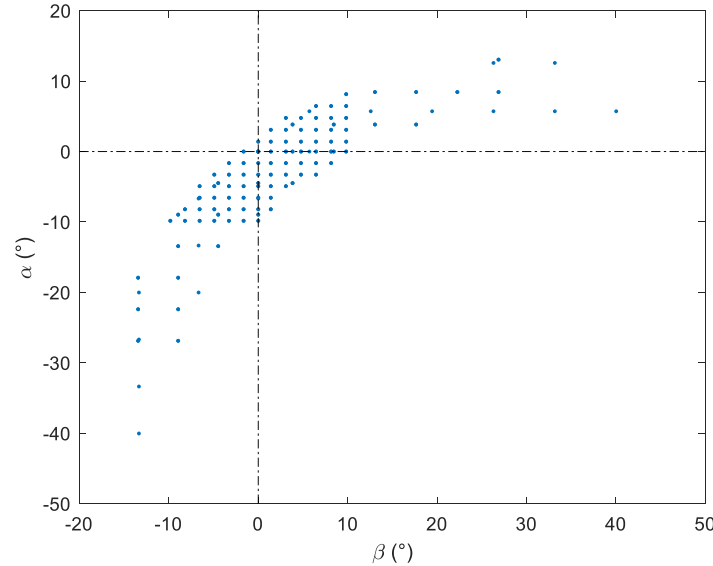


Figure 4 :  $\alpha = f(\beta)$

### 3 MODELLING

During the last decade many models were developed to calculate vibroacoustic indicators. This paper is mainly focused on the STL as the acoustic indicator. Considering an incident plane wave impinging a structure with a specific angle, this will create 3 other waves corresponding to a reflected, transmitted and absorbed wave as illustrated in Fig 5. The STL is defined with the ratio  $\tau = |W_t / W_i|$  which is the ratio between the acoustic power of the transmitted and incident wave and could be obtained for specific angles (Eq. 1).

$$STL(\theta, \phi, \omega) = -10 \log_{10} \frac{W_t}{W_i} \quad (1)$$

The STL is also calculated for a diffuse field by the integration over all angles  $\theta \in [0^\circ, 90^\circ]$  and  $\phi \in [0^\circ, 360^\circ]$  and yield to Eq. 2.

$$STL_d(\omega) = \frac{\int_0^{2\pi} \int_0^{\theta_{max}} \tau(\omega, \theta, \phi) \sin(\theta) \cos(\theta) d\theta d\phi}{\int_0^{2\pi} \int_0^{\theta_{max}} \sin(\theta) \cos(\theta) d\theta d\phi} \quad (2)$$

In 2016, two methods released [15, 16] using the nodal surfaces and the Transfer Matrix Method (TMM) concept combined with the WFEM respectively. They allow to model complex

structures without homogenization. More recently, [17] added their contribution by developing a hybrid wave-based method with finite element to add more complexity to the structure as resonators. It is possible to model other type of fluid on both sides of the structure such as strong fluid-structure interaction. In this paper, the method developed in [16] will be used. Indeed, the computational cost is drastically reduced since the skins are modeled using the analytical formulation for simple plate. The core is modeled with Ansys apdl using SHELL elements and MATLAB for post processing. It is assumed an infinite panel, real wavenumbers and that the structure is excited by plane waves with the angles of incidence and reflection equal. The principle of this method is illustrated in Fig. 6.

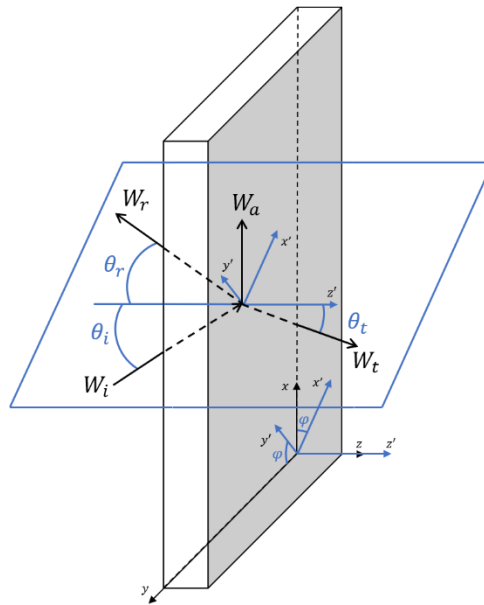


Figure 5 : Plane wave incidence, reflection, transmission and absorbed at the interface of a sandwich panel.

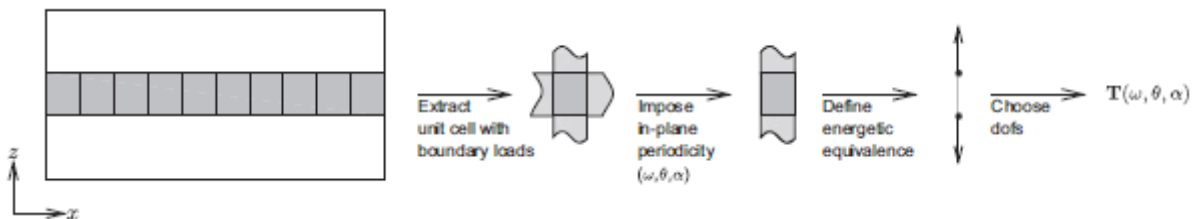


Figure 6 : Procedure for applying the method developed in [16]

Finally, to perform the parametric analysis two options are chosen for simplification. Firstly, due to the orthotropy of the structure resulting from the honeycomb core, it is not necessary to calculate the diffuse field. From the dispersion curves of the standard case corresponding to the rectangular core, bending waves reveals the direction  $x$  as critical to determine the acoustic efficiency of the structure. It is shown that the intersection with the acoustic wavenumber and bending waves occurs in the direction  $x$ . Thus, the STL will be calculated for an angle  $\varphi = 0^\circ$  and  $\theta = 45^\circ$  exciting the structure in its  $x$ -direction only. In addition, the target indicator is

defined as the integration of the STL over the frequencies as it is done in [18]. The more the value is high the more the structure is considered acoustically efficient.

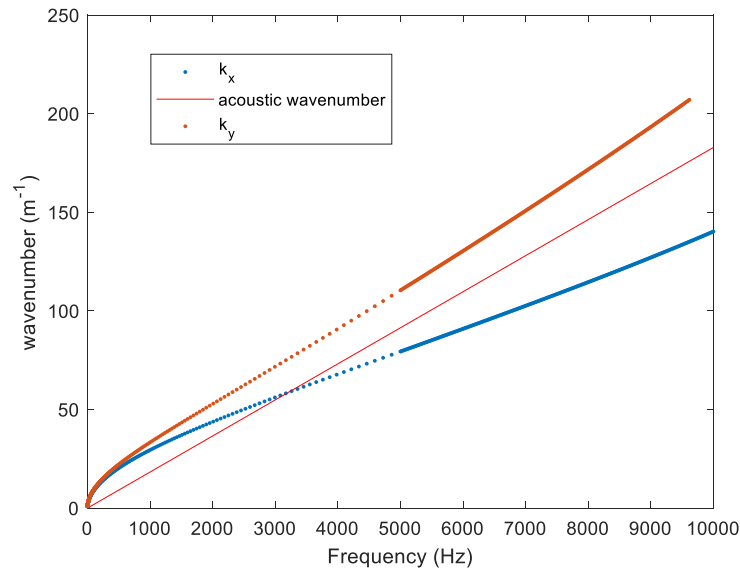


Figure 7 : Bending waves of the standard case (rectangular core)

### 3 PARAMETRIC SURVEY

The first result was obtained having all configurations with different values of  $a_3$ . It is shown in Fig. 8 that a quasi-symmetry occurred related to the chosen parametric model. As it can be noticed, the parameter  $a_3$  has a strong influence on the STL and the highest values of STL is obtained when  $a_3 = Lx/4$ . The next steps of the parametric analysis are carried out with  $a_3 = Lx/4$ .

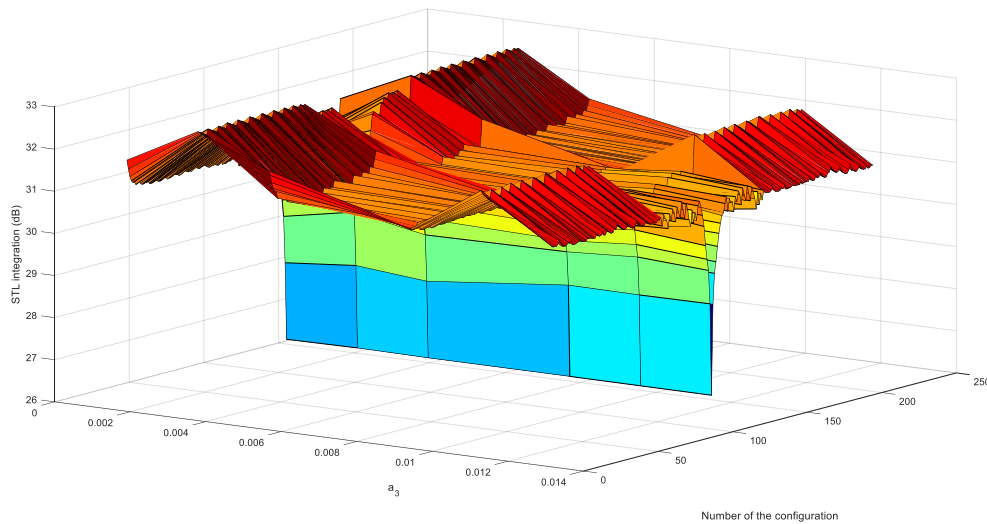


Figure 8 : Effect of the parameter  $a_3$  on all configurations



Fig. 9 shows the effect on the STL of the angles  $\alpha$  and  $\beta$  for different values of  $a_1$ . The influence of the angles is highly dependent on the value of the parameter  $a_1$ . The angles  $\alpha$  and  $\beta$  become critical parameters when  $a_1 = Ly/4$ . Consequently, for such configuration it is necessary to make a wise choice on the angles. The highest values of the STL are obtained with  $a_1 = 1,25$  mm and  $a_1 = 6,25$  mm.

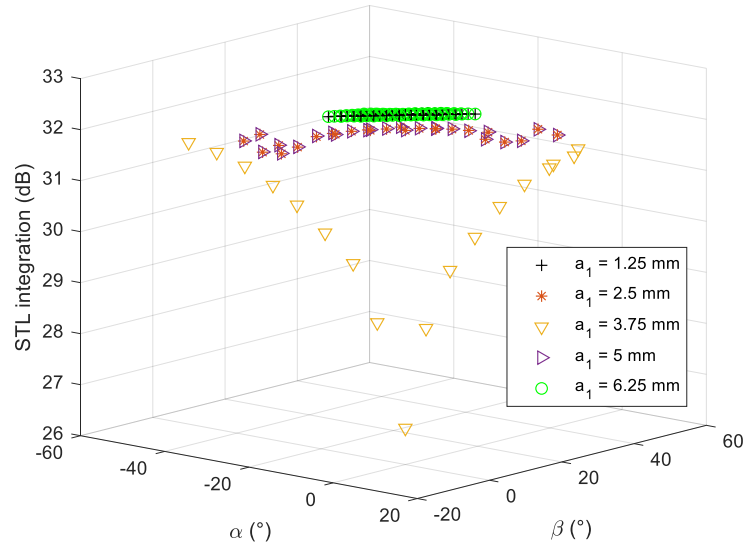


Figure 9 : Effect of the angles of the core  $\alpha$  and  $\beta$  with specific values of the parameter  $a_1$ .

Finally, the effect of the pair  $(\alpha, \beta)$  is illustrated in Fig. 10. It is shown that depending on the value of the STL, the pairs  $(\alpha, \beta)$  correspond to a linear function in which the value of the intercept has a critical influence. The highest value of STL occurs when the intercept is the lowest and the pairs  $(\alpha, \beta)$  are highlighted in Fig. 10.

From this parametric study the optimized configuration can be listed in the following Tab. 1. with  $a_1$  and  $a_2$  equal to 1,25 mm or 6,25 mm and  $a_3 = Lx/4$ . Since the unit cell size is 15 mm by 15 mm, the angles are almost neglectable and could be considered as  $0^\circ$ . Nevertheless, the optimized unit cell with the highest STL value correspond to  $(1,4^\circ, 0^\circ)$ .

**Table 1:** Pairs of  $(\alpha, \beta)$  for the optimized unit cell.

$\alpha$ (°)	-4,9	-3,3	-1,6	0	1,4	3	4,8
$\beta$ (°)	-6,5	-4,9	-3,2	-1,6	0	1,4	3

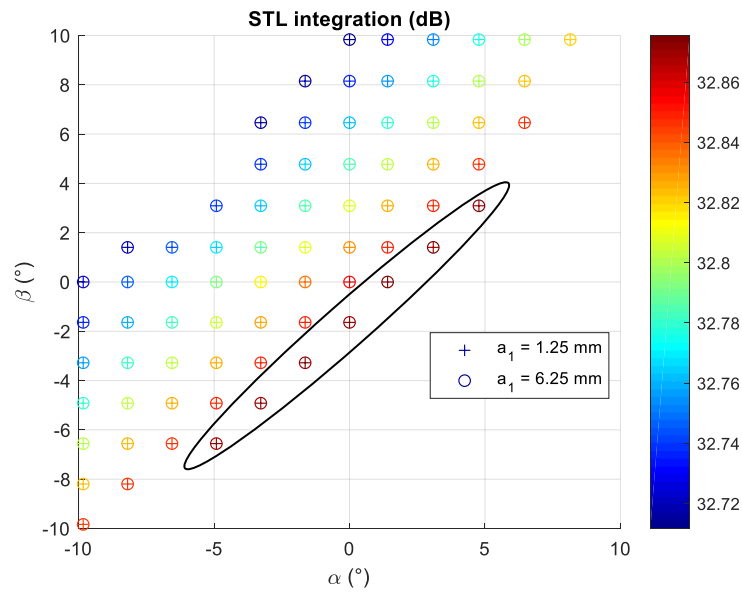


Figure 10 : Influence of the pair  $(\alpha, \beta)$  given with  $a_1 = 1,25$  mm and  $a_1 = 6,25$  mm.

#### 4 OPTIMIZED VS STANDARD STRUCTURE

Thanks to the parametric survey, it is then possible to compare the optimized structure with the standard rectangular core. The Fig. 11. shows the great improvement obtained with the multi-layer core system in all the frequency range. The coincident frequency is shifted to higher frequencies.

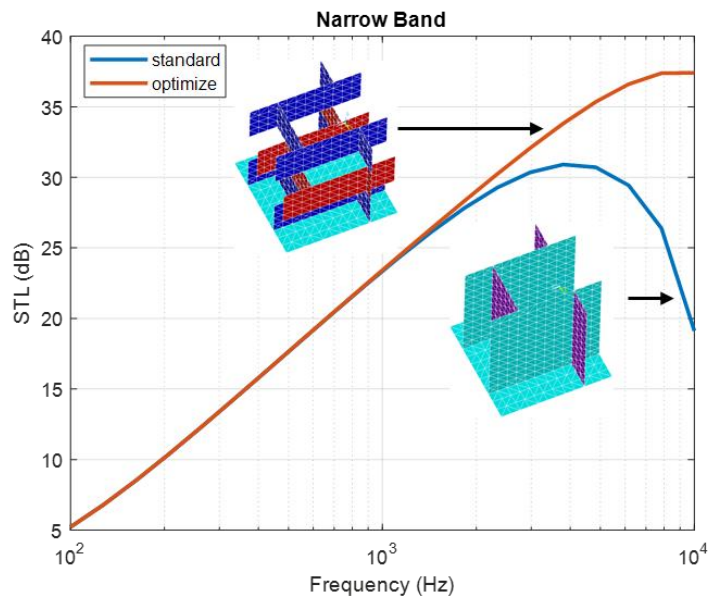


Figure 11 : Comparison of the STL ( $\theta = 45^\circ$  and  $\varphi = 0^\circ$ ) of the optimized structure with the standard case.

This result is confirmed with the comparison of bending waves in Fig. 12. The multi-layer core has lower equivalent mechanical properties in both direction x and y and lead to an intersection with the acoustic wavenumber to a higher frequency. The acoustic wavenumber is calculated for a diffuse field and the intersection correspond to the critical frequency. Consequently, the optimized structure should be still acoustically efficient in a diffuse field.

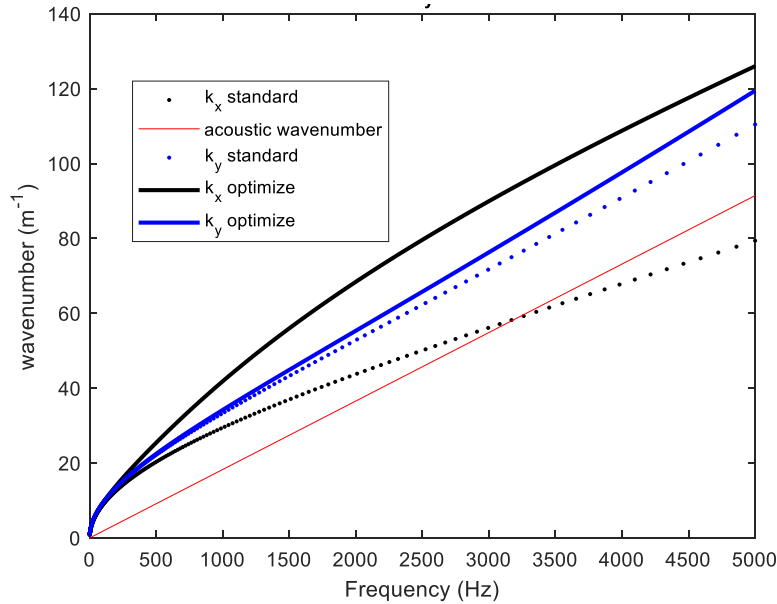


Figure 12 : Bending waves comparison of the optimized and standard structure.

Finally, the mechanical and acoustical properties for both structures are summarized in the following table (Tab. 2).

**Table 2:** Mechanical and acoustical properties.

	standard	optimized
Compression modulus (MPa)	227	92
Transition Frequency (Hz) (ftx, fty)	(2910, 1694)	(1388, 251)
STL integration (dB)	26,71	32,88

The compression modulus is calculated along z-axis. As it is noticed, the improvement of the STL goes along with a reduction of the compression modulus and the transition frequency in both directions. Multi-layer core systems show a great interest in terms of acoustic properties while mechanical properties seem to be lower than a standard one core unit cell. These results were obtained without altering the mass which is a critical parameter especially in the aerospace industry.

## 5 CONCLUSIONS

This paper has been focused on the study of multi-layer core topology systems made of 3 layers with a top and bottom rectangular core and a random middle core. It has been shown that this new kind of structure involves new geometrical parameters to be considered. A parametric survey has been suggested to study the influence of this geometrical parameters on the random core. The parameter  $a_1$  and  $a_2$  were considered equal. The STL has been chosen as the target acoustic indicator and a WFEM combined with the TMM method has been used to model the unit cell.

It occurs through the analysis that all parameters seem to have an interaction with the other and could become critical in some configurations. The parameter  $a_3$  have a strong effect on the STL and is maximum when  $a_3 = Lx/4$ . In addition, the pair  $(\alpha, \beta)$  have an impact on the STL when  $a_1 = a_2 = Ly/4$  and their influence decrease when  $a_1$  get close to 0 or  $Ly/2$ . Moreover, after fixing  $a_1 = 1,25$  mm or  $6,25$  mm, it was shown that the pair  $(\alpha, \beta)$  turned out a linear relationship according to the value of STL. Thereby, the optimized pair  $(\alpha, \beta)$  corresponded to the equation with the lowest intercept. Consequently, an optimized structure with the same surface density of the standard rectangular core was obtained as well as the comprehension of the influence of each parameter of the parametric model.

Ultimately, the parametric analysis may introduce new target indicators as mechanical and vibroacoustic indicators. In addition, this parametric model proposes some tools to verify the influence of each parameter and could be applied to other standard structure as hexagonal and auxetic core widely spread in the industry. Finally, some vibroacoustic indicators as the transition frequency seems to be strongly influenced by the geometry of the multi-layer core and should be studied.

## ACKNOWLEDGEMENT

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