Vibro-acoustic analysis of additively manufactured acoustic metamaterial via CUF adaptive finite elements

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Keywords: Aircraft Noise, Vibro-acoustics, Acoustic Metamaterials, Carrera's Unified Formulation

Abstract. In the field of noise and vibrations control inside the cabin, passive noise solutions coupled with the development of new unconventional materials, called Acoustic Metamaterials (AMMs) can be very promising to stop incoming noise and guarantee the passenger's comfort without an increase in aircraft weight. Within the framework of Carrera's Unified Formulation (CUF), we study the acoustic properties of double pierced AMM plate printed with Fused deposition modelling technique (FDM). The influence of several geometrical parameters is investigated, such as the size and location of the holes and the perforation ratio. The properties of this AMM are derived from vibro-acoustic analyses of the finite element software, Mul2, developed by *Politecnico di Torino*, that exploits the CUF. In order to study the AMM complex structure in the CUF framework, the Adaptive finite elements are exploited. This new class of 2D elements, recently developed, allows us to model with shell elements the AMM structure, which presents several discontinuities in the mid-surface due to the presence of corners and internal cavities.

Introduction

The problem of noise in commercial aircraft is usually related to the emission of sound waves outwards, resulting in noise pollution problems in areas near airports or landing and take-off paths [1]. However, noise is also an internal problem of the aircraft, where sound waves follow paths internal to the aircraft structures or are generated by sources that are already internal (e.g., the air conditioning system) [2]. Internal noise negatively affects the comfort of passengers and crew during flight, weakening the competitiveness of the aircraft compared to other methods of travel.

In order to decrease the amount of noise in the passenger cabin, there are several proposed solutions. The simplest solution in terms of both implementation and logic leads to shielding the passenger cabin by means of insulating panels in the cavity between the fuselage and the cabin panel [3]. In this work, we focus on the low and medium frequencies that are traditionally difficult to shield with conventional materials. For this reason, it was decided to use materials with special acoustic properties, acoustic metamaterials (AMMs). With AMMs, high absorption coefficients in a certain frequency range can be achieved with lightweight structures by using appropriate elementary cell geometries repeated periodically in the absorber panel. However, these new materials present problems related to the field of numerical analysis compared to the results of the current structure. The use of numerical models, the Finite Element Method (FEM) for the low and medium frequencies, is essential both in the preliminary stages to have extensive design flexibility, but even more in the later stages to study the AMM in the aircraft environment, where the analysis is scaled from the characterization of a simple plate to that of several panels in the aircraft fuselage.

The major problem is in the process of numerical homogenization of the AMM, which brings with it the hypothesis of a perfect repetition of the elementary cell. Small manufacturing errors can lead to significant differences between experimental and numerical results. To avoid this problem, the following work has chosen to use an AMM produced with additive printing based on literature [4], that can guarantee high precision in the production of the AMM and the study of a geometry difficult to obtain with conventional production methods.

A second problem is the numerical method used in the finite element field to solve the vibro-acoustic problem. Indeed, as will be further described, the proposed AMM has internal cavities pierced with the presence of double fluid-structure interfaces that would require the use of solid elements with conventional FEM methods. In order to avoid an excessive number of Degrees of Freedom (DoF) without losing accuracy, Carrera's Unified Formulation (CUF) has been chosen [5], which allows us to exploit different theories for plates, both Equivalent Single Layer (ESL) and Layer Wise (LW). The geometry of the material also required integration into the formulation of a new class of elements, the Adaptive finite elements [6, 7], to handle corners and intersections between the various elements.

Vibro-acoustic problem in the CUF-FEM framework

The vibro-acoustic problem that describes the AMM of this work is that it includes an elastic structure coupled to internal cavities. The following system must then be resolved before information on dynamic behaviour and Transmission Loss (TL) can be obtained:

$$\begin{bmatrix} -\omega^2\boldsymbol{M}+\boldsymbol{K} & \boldsymbol{S} \\ -\rho_f\omega^2\boldsymbol{S} & -\omega^2\boldsymbol{Q}+\boldsymbol{H} \end{bmatrix}\cdot\begin{Bmatrix} U \\ P \end{Bmatrix}=\begin{Bmatrix} \boldsymbol{F} \\ 0 \end{Bmatrix}$$

where we have the mass matrix **M**, **Q** and stiffness **K**, **H** of structure and fluid respectively, the coupling matrix **S** and the vector of the external loads on the structure **F**. The previous matrices and vectors are defined according to the fundamental nuclei formulation [8]. The vectors of the unknown are U and P, the three displacements and the pressure respectively. The properties of the fluid are defined by the density ρ_f and speed of the sound c_f, while those of the structure are defined by the elasticity matrix **C**. The problem is solved in the frequency domain, represented by the angular frequency ω. In the FEM approximation, the unknowns are the nodal values, the transition to the continuous field is guaranteed by the shape functions N.

According to the CUF, the three-dimensional field of a shell can be split into a two-dimensional field on the shell plane and an expansion on the thickness F_τ, called thickness function [5]. The choice of thickness functions leads to the use of different plate models. In this work, the Lagrange polynomials are used to have a Layer Wise approach. In addition, the integration of the Adaptive finite element leads to the use of a new three-dimensional shape function L, which combines the shape and thickness functions, in the calculation of the integral and the Jacobian. Then the displacement field is defined by the following equation:

$$u_\tau^k(x,y,z)=\left(N_iF_\tau^{ki}\right)\boldsymbol{U}_{\tau i}^k=L_{\tau i}^k(x,y,z)\boldsymbol{U}_{\tau i}^k$$

For the pressure field, being defined by three-dimensional elements, the conventional FEM formulation is applied.

Acoustic solution

The design of sandwich panels has been the subject of various studies during the past decades [9]. Since the panels' faces are not designed to absorb sound, the choice of the core turned out to be particularly crucial for the reduction of noise [10]. Instead, by using plates with small holes and an air cavity in the centre, the so-called micro-perforated panels (MPPs), the sandwich plate can have a positive impact on noise reduction, improving sound absorption. The research by Meng et al. [4] is chosen as a reference since it focuses on the influences of holes' diameter of an additively produced AMM.

It comes to light that the porosity, location, and diameter of the holes all affected the sound transmission loss. Following this direction, various AMM models have been developed to comprehend how the noise operates at low- to middle-frequency levels in various design parameter combinations. The dimension of the holes, the position of the holes, and the perforation ratio are the three main parameters of interest for the model definition in this study. The porosity or perforation ratio $PR_{\%}$, which is typically given in percentages, describes how much of a plate is made up of holes:

$$A_h = PR_{\%} \cdot A_e$$

where A_h is the circular area of the holes and A_e is the elementary cell area.

Then, a series of models are created, shown in Tab. 1 and the third one is reported in Fig. 1(a). The production method chosen is the fused deposition modelling technique (FDM) with a Fortus 250 mc and ABS Plus p430, as a material, on which preliminary studies have already been carried out [11-13]. Although it may not be one of the most precise printing techniques, it allows a sufficiently robust structure to be obtained and to direct the filament deposition path to increase the accuracy of the AMM's holes, especially on the oblique plates. All models were printed correctly except the fourth due to the excessively small size of the holes (i.e., 0.5 mm). Fig. 1(b) shows one of the printed models.

Table 1: AMM models' properties, the first model is not pierced.

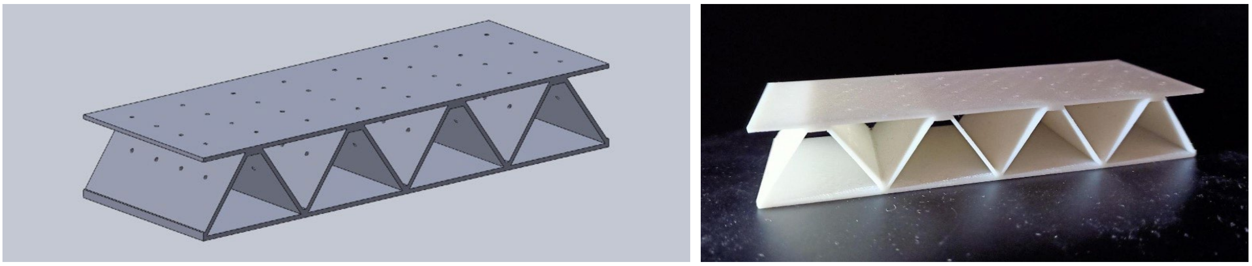
Models	AMM density [kg/m^3]	$PR_{\%}$	Holes diameter [mm]	Holes location
1	1040	-	-	No holes
2	1039	0.349	1	Upper plate
3	1037	0.349	1	Upper plate & core
4	1037	0.349	0.5	Upper plate & core
5	1037	0.698	2	Upper plate & core
6	1035	0.175	1	Upper plate & core
7	1039	0.175	1	Upper plate & core

The numerical study of the models allows us to derive a priori the TL. In order to avoid errors, the model has been pre-validated by comparing its natural frequencies with those obtained from commercial software. Then, a direct frequency analysis is performed on a simply supported AMM plate, loaded with constant amplitude load (1 N). The results in terms of TL show that the presence of the holes, their size and position is decisive in defining the acoustic behaviour of the AMM. Among the various results reported in a complete way in Rossi's work [14], it is interesting to note that the third and fifth models (which have the same homogenized density) have significant TLs between 1000 and 1900 Hz in Fig. 2, although for the fifth with several peaks and discontinuities. While the fundamental frequency of the seventh model is the highest among the six models. The fourth model was not produced; therefore, it was not studied.

Conclusions

This work is intended to provide a preliminary basis for further study of AMMs produced with additive techniques for noise reduction in aircraft. The results demonstrate the excellent acoustic properties of these structures and the possibility to study them with innovative numerical methods.

In the future, it is necessary to validate the numerical results through experimental tests in the anechoic chamber or with an impedance tube and then scale the problem to study the AMM in the working environment. Finally, FDM is only one of the available additive techniques. The advantages or disadvantages of other technologies for AMM production need to be evaluated with appropriate research.



(a) (b)

Figure 2: The AMM designed in this work and based on the work by Meng et al [4]. (a) The third model isometric representation. (b) The first model after the production process.

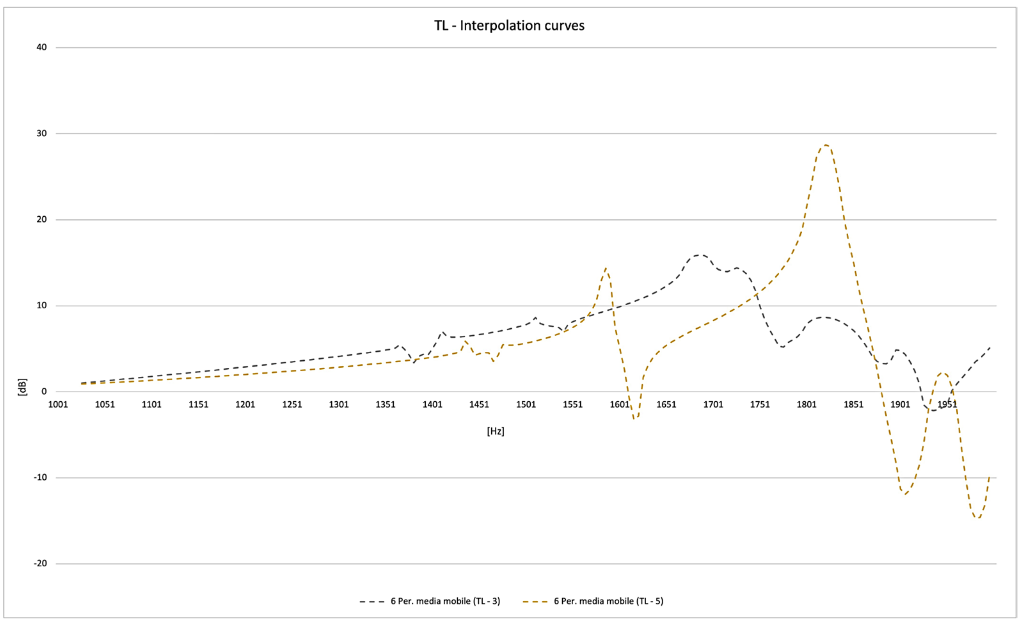


Figure 2: The average TL [dB] from 1000 Hz to 2000 Hz for the third model (grey line) and the fifth one (yellow line).

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