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A MULTIDISCIPLINARY METHOD FOR SIMULATION GUIDED DESIGN OF MECHANICAL STRUCTURES

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Abstract — Composite sandwich panels are often used in aerospace industry for their high bending stiffness to weight ratio and vibration damping properties. All structural, vibrational, environmental, and economic aspects are considered during the design process. This article presents a multidisciplinary method for simulation guided design of mechanical structures, mainly focusing on vibro-acoustic performance of sandwich floor slabs used in aircrafts. Vibration behaviour of the floor slab strongly depends on the geometry, material properties, and boundary conditions. Python programming language is used to fully parameterize the structure, to automate multiphysics analyses and to develop a user interface. It allows to combine computer-aided design scripting, finite element software scripting packages, numerical calculus and postprocessing features. Numerical simulation is performed to estimate natural frequencies of the complex geometry of the floor slab. Harmonic analysis is performed to determine the forced vibration response. Acoustic radiated power is deduced from the velocity continuity of the elastic surface and the acoustic particles on the surface. The elementary radiators method is used to calculate the acoustic radiated power of complex geometry. The multidisciplinary and parameterized approach allows to determine the main design parameters to guide the design engineers.

Keywords – vibration analysis; sandwich panel; radiated power; numerical analysis

I. INTRODUCTION

Sandwich composite panels are layered structures made of two external thin layers known as skins, and a thick internal layer referred to as the core. The skins and core are bonded together using adhesive layers (Fig. 1). These structures are widely used in the transportation industry due to their high bending stiffness to weight ratio [1], which allows for significant weight reduction while maintaining structural performance. However, reducing the weight can also lead to increased vibrations, which can have negative impacts on human health [2], system integrity or fatigue damage [3]. To mitigate these effects, vibration-damping core materials such as foam are being increasingly used to reduce the vibrations [4]. Moreover, certain polymer foams can be manufactured from recycled materials, making them a more environmentally friendly alternative to the traditional metals [5]. In that context, the design of sandwich structures must take into account the coupled complex relationships between structural, vibration, acoustic, and environmental aspects.

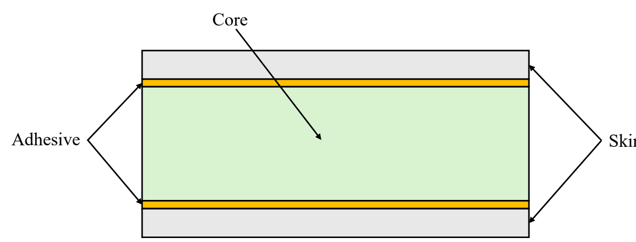


Figure 1. Sandwich panel section.

Unlike thin composites, sandwich panels require the consideration of shear deformation due to their unique structural configuration. Reissner-Mindlin, i.e., a first-order shear deformation plate theory, is commonly used to analytically describe the deformation of these structures [1], [6]. A comprehensive review of theories applied to bending, buckling, and free vibration of sandwich beams was presented by Sayyad et al. [7], who highlighted the finite element method (FEM) as the most widely used approach in structural analysis. Sandwich panels can be categorized into different groups including [1], [8]: corrugate, honeycomb, cellular or balsa cores. The mechanical properties can be highly non-homogeneous depending on the specific core group. To predict the panel properties and failure, numerical simulations are often employed [3]. For instance, Xie et al. [9] investigated the flexural properties of foam-filled lattice composite sandwich panels, while Wu et al. [10] studied lightweight sandwich panels with the focus on corrugated-pyramidal truss core using the analytical models and finite element simulations.

Fahy [6] identified two primary areas of study for vibroacoustic performance of sandwich panels. Firstly, sound transmission loss refers to the panel's ability to reduce noise. Proença et al. [11] developed a numerical model of a building floor and confirmed that FEM can provide accurate results for sound transmission at low frequencies. However, their study revealed that the investigated lightweight panel did not meet the acoustic requirements set in the building codes. Secondly, the radiation problems investigate the acoustic power radiated by vibrating elastic surfaces. Analytical solutions for acoustic radiated power exist for simple geometries, materials, and boundary conditions [6]. For example, Zaman et al. [12] investigated the acoustic radiation power for simply supported homogeneous plate. For a complex geometry, Fahy [6] presented the elementary radiator method to estimate the acoustic radiated power from surface velocity. FEM is widely used to study structures with complex geometries and inhomogeneous materials. Shishir et al. [13] studied a polymer pin-reinforced foam core sandwich. They investigated the impact of pin diameter and density on free vibration response through experimental and numerical methods. FEM was used [4] and [14] to calculate the panel surface velocity, which is then used to apply the elementary radiator method to calculate the acoustic radiated power. Reddy et al. [4] showed the possibility of reducing sound power level by increasing the inherent material damping of the core. They compared the acoustic characteristics of sandwich panels with fiber reinforced polymer core and aluminum skins.

Environmental considerations have become increasingly important in design and the development of sustainable materials. Oliveira et al. [15] provided a comprehensive review of green sandwich structures, presenting eco-friendly solutions for skin, core, and adhesive materials. In a related study, Oliveira et al. [16] investigated the use of upcycled bottle caps as core material in sandwich panels, combined with sustainable components. Their research demonstrated the potential of ecological alternatives for skin and adhesive by comparing the traditional aluminium and epoxy polymer with the recycled PET-bottle foil skin and a castor oil bio-polyurethane. Sergi et al. [8] explored the use of agglomerated cork as core material, which offers good damping properties similar to those of polymer foam. Recently, fully recycled PET closed-cell foams have become available [5], providing a more environmentally friendly alternative than the traditional polymers used to produce core foams such as polyurethane (PUR), polystyrene (PS), and polyvinylchloride (PVC) [8]. These developments highlight the growing trend towards sustainable materials and structures in the field of composite sandwich panels.

Current literature indicates that sandwich panels are active research subject in structural, vibration, acoustic and environmental fields. Numerical simulation is a widely used tool to predict sandwich structure properties and behaviour. This study presents a multidisciplinary approach to simulation-guided design of aircraft floor slabs, leveraging the capabilities of Python and commercial finite element software, to improve the efficiency of the mechanical design process. By coupling these tools, multiple scenarios can be analyzed and compared across different aspects, enabling the identification of the most influential design parameters and guiding the designer in the preliminary design phase. The focus of this article is on the vibroacoustic aspect, with a particular emphasis on a floor slab featuring either an aluminium honeycomb or polyethylene terephthalate (PET) foam core material. The numerical approach employed in this study aims at providing a comprehensive understanding of the design parameters impacting the vibroacoustic performance of the floor slab, ultimately informing the design process and contributing to the development of more efficient and effective aircraft floor slab structures.

II. METHODOLOGY

A. Multidisciplinary method for simulation guided design

A good preliminary design can significantly reduce time and costs in the structural design process. By considering all major aspects of design (structural, vibration, environmental, cost, etc.) from the start, exchanges between different departments and unexpected surprises during a project can be minimized. With this goal in mind, a multidisciplinary method for simulation guided design has been developed for aircraft floor slabs.

Python language-based micros are more and more integrated into commercial software packages. Computer-aided design (CAD) software allows to automate the design tasks using Python. Additionally, finite element software allows for automated model creation using Python. New packages facilitate model automation and analysis without interaction with the software user interface. Models can be fully parametrized, and a custom user interface can be developed to retrieve the design parameters. This approach enables the seamless integration of powerful Python packages for post-processing, adding personal code of calculus, generating reports, using databases and more. Fig. 2 illustrates the organization and developed methodology in this study, which consists of two main modules. The first module is designed for creating and simulating new scenarios. The second module is dedicated to post-processing and comparison of different scenarios.

The design process begins with a user interface that allows retrieving the design parameters such as material, geometry, connections, pads as well as scenario characteristics including load and frequency range of interest. Then, CAD scripting is used to create the geometry based on the user-provided data. Finite element software is used to define the finite element model by importing material and geometry. Pads and bolt connections between the support beams and floor slab are created. Various structural, modal, harmonic, transient analyses are run, and load and boundary conditions are automatically applied. Then, analyses are carried out and all data of the scenario necessary for post-processing are saved including stress, displacement, velocity, acceleration. Specifically, results of harmonic analysis are used for vibroacoustic calculations. Mesh and the velocity response of the floor slab are used in a custom code to perform further calculations.

The concept of object-oriented programming is used to create a database of scenarios, where each scenario is represented as an object with its characteristics such as maximum stress, failure criteria, natural frequencies, mode shapes, displacement, velocity and acceleration response. By associating environmental and economic information with the materials used in each scenario, the method can do carbon impact and cost comparison for different designs. Hence, the method can be used for sensitivity analysis as well as for comparing completely different scenarios. The post-processing module allows the design engineers to easily plot the comparison graphics and see the impact of design parameters on multiple aspects simultaneously. These facilitate the decision-making process as designers can quickly identify the most critical factors affecting their design. The main goal of this method is to save time in the design process. It is essential to note that vibroacoustic performance of each scenario is solely based on numerical simulations, and the results should be considered relative from one to another.

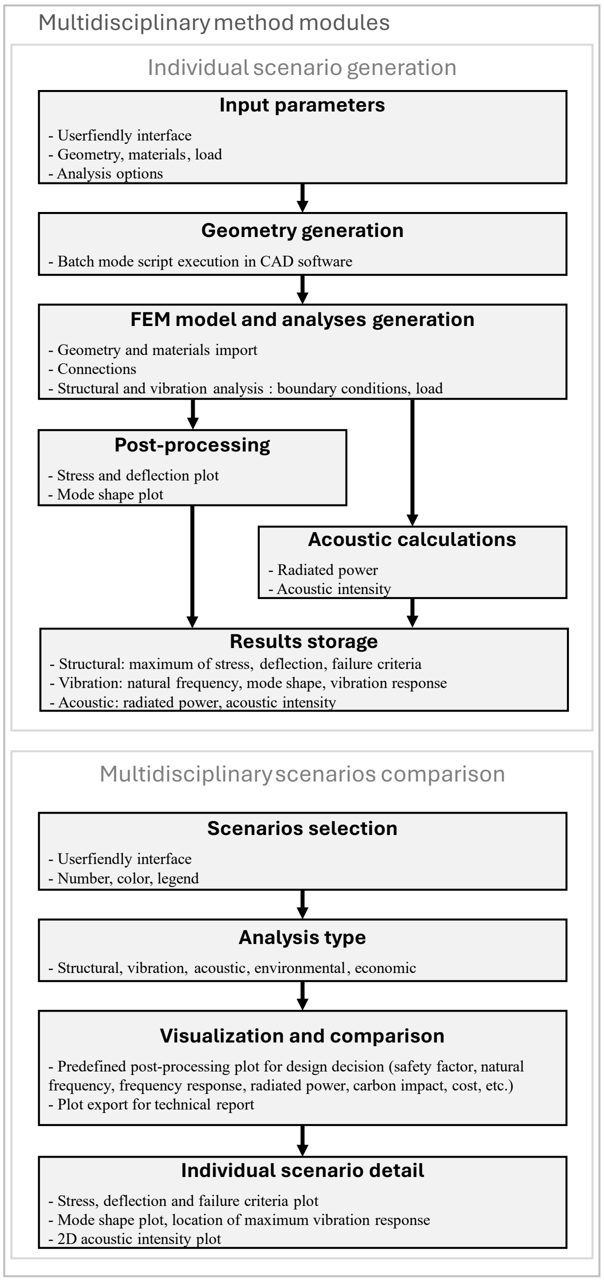


Figure 2. Overall developed approach.

B. *Studied structure*

The structure under investigation is the floor slab of an aircraft simulator, which consists of a sandwich panel made of two aluminium skins and a foam or honeycomb core material. The floor slab length to thickness ratio is 65. The core to skin thickness ratio is 28. The slab is supported by aluminium beams as shown in Fig. 3. The presence of cutouts in the slab for fixing additional structures introduces a complex geometry to the structure. Beams and floor slab are attached together through bolt connections. Isolation pads are also positioned between them. When the pads are in place, a gap exists between the floor and the beams, whereas in their absence, the floor is in direct contact with the beams. The support beams are fixed to a rigid platform, as indicated by the red regions in Fig. 3. When the rigid platform is excited to simulate a specific flight scenario, the resulting loads are transmitted to the vibration prone beams and floor slab. Properties of various materials that comprise the structure are summarized in Table 1.

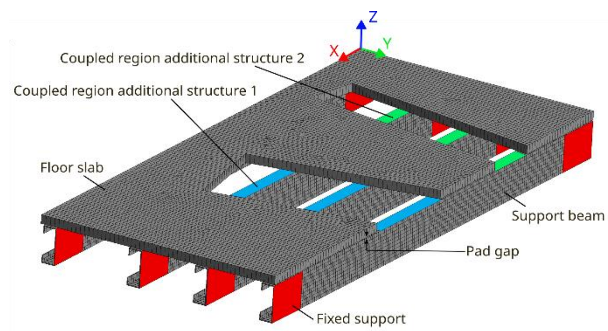


Figure 3. Structure and model description.

TABLE 1. MATERIAL PROPERTIES

Properties	**Aluminum facesheets** [17]	**Aluminum honeycomb** [18], [19]	**PET foam** [20]
E_x (MPa)	70300	0.4	32
E_y (MPa)	70300	0.4	32
E_z (MPa)	70300	1438	32
G_{xy} (MPa)	-	0.2	14
G_{xz} (MPa)	-	380	14
G_{yz} (MPa)	-	170	14
v_{xz}	0.33	0.99	-
v_{yz}	0.33	0.0001	-
v_{yz}	0.33	0.0001	-
Density (kg/m^3)	2680	58	75

C. *Numerical model*

Finite element analyses (FEA) of the floor slab are carried out using the commercial finite element solver. Aluminum support beams and the sandwich panel are modelled using 4-node quadrilateral shell elements with six degrees of freedom at each node. Bolt connections are modelled using 2-node elements with six degrees of freedom at each node and multipoint constraint (MPC) equations. Finally, pads are modelled using spring-damper elements which are defined by a longitudinal stiffness of $465\ kN/m$ and a damping of $1070\ N.s/m$. If pads are not considered, no separation contact is defined between the floor and beams. In that case, bolt connections are modelled as a joint with MPC equations.

Aluminum support beams are fixed at their extremities, assuming an infinitely rigid structure around the floor slab. As the pads are modelled as unidirectional elements, only the vibrations in the vertical direction (Z) of the floor slab are simulated. Transversal vibration is also responsible for noise radiation. Vertical acceleration is introduced as base excitation at the boundary condition location. Additional structures are assumed to be perfectly rigid and represented by distributed mass and coupling equations on the support beams. Masses are applied to represent the additional features respectively for region one and two (Fig. 3).

Longitudinal stiffness and damping for the pads are based on their preload. As no experimental study has been carried out on the floor structure, a constant damping value is assumed over the entire frequency range of interest (0-1000 Hz). The value is fixed considering a typical damping of mechanical structure of 2% and an additional damping depending on the core material. Finally, the constant damping ratio for harmonic analysis is 4% for the PET foam floor slab and 2.2% for the honeycomb floor slab.

D. *Vibroacoustic calculations*

The vibroacoustic analysis mentioned in the methodology (Fig. 2) is presented below. A free vibration analysis is carried out to predict the natural frequencies of the structure. The eigenvalue problem (1) is solved to determine the natural frequencies and the corresponding mode shapes.

$$(K - \omega_n^2 M)\phi_n = 0 \tag{1}$$

where K is the stiffness matrix, M is the mass matrix, ω_n is the circular natural frequency, and ϕ_n is the mode shape vector. Harmonic analysis is carried out to determine vibration amplitude and normal velocity response over the floor slab. Equation (2) is solved using the modal superposition method.

$$M\ddot{U} + C\dot{U} + KU = F(t) \tag{2}$$

where C is the damping matrix, $\ddot{U}$, $\dot{U}$ and U are the acceleration, velocity, and displacement response, respectively, while $F(t)$ represents the excitation. By knowing the velocity response $\dot{U}$ over the floor slab, the Rayleigh integral [6] is used to calculate the complex pressure at distance r and a time t as given in equation (3).

$$p(\vec{r},t) = \frac{j\omega\rho_0}{2\pi} e^{j\omega t} \int_s \frac{v_n(\vec{r_S}) e^{-jkR}}{R} dS \tag{3}$$

where ρ_0 is the air domain density, ω is the circular frequency of the forced excitation, r_S is the centre position of the plate's elementary surface dS, v_n is the normal velocity, k is the acoustic wave number and R the distance defined as $|\vec{r} - \vec{r_S}|$. Under the assumption of baffled panel, the elementary radiator method [6] is implemented in the Python code. The mesh generated by the finite element software is used to discretize the floor slab geometry into N elements (radiators) and the harmonic analysis is used to predict the normal velocity of each element. Therefore, Rayleigh integral is applied to each element. Complex velocity amplitude of the entire floor slab can be written in vector as given in equation (4), where v_{ei} is the complex normal velocity of element i. Complex sound pressure amplitude acting on each element can also be represented as a vector in (5).

$$\{v_e\} = [v_{e1}\ v_{e2} \ldots v_{eN}]^T \tag{4}$$

$$\{p_e\} = [p_{e1}\ p_{e2} \ldots p_{eN}]^T \tag{5}$$

Assuming small dimensions of the element compared to structural and acoustic wavelength, the total radiated acoustic power can be estimated [6] as the summation of the powers radiated by each element P_{ei} (6). Then, if the mesh is structured and the area A_e of each element is almost constant, the total radiated power is expressed in (7), where $\{\ \}^H$ is the conjugate transpose operator.

$$P_{ei} = \tfrac{1}{2} A_e Re\{v_{ei}^* p_{ei}\} \tag{6}$$

$$P(\omega) = \sum_{i=1}^{N} \frac{1}{2} A_e Re\{v_{ei}^* p_{ei}\} = \frac{A_e}{2} Re\{\{v_e\}^H \{p_e\}\} \tag{7}$$

From (3), sound pressure acting on element i is $p_{ei} = (j\omega\rho_0 A_e e^{-jkR_{ij}}/2\pi R_{ij}) v_{ej}$. Introducing the impedance matrix $[Z]$ between the velocity $\{v_e\}$ and pressure $\{p_e\}$ [6], the radiated power can be rewritten as (8). Knowing that impedance matrix is symmetric, radiated power can be expressed as (9) with a radiation resistance matrix $[R]$ (10).

$$P(\omega) = \tfrac{A_e}{2} Re\{\{v_e\}^H [Z] \{v_e\}\} \tag{8}$$

$$P(\omega) = \{v_e\}^H [R] \{v_e\}\} \tag{9}$$

$$[R] = \frac{\omega^2 \rho_0 A_e^2}{4\pi c_0} \begin{bmatrix} 1 & \frac{\sin(kR_{12})}{kR_{12}} & \cdots & \frac{\sin(kR_{1N})}{kR_{1N}} \\ \frac{\sin(kR_{21})}{kR_{21}} & 1 & \ldots & \vdots \\ \vdots & \ldots & \ddots & \vdots \\ \frac{\sin(kR_{N1})}{kR_{N1}} & \ldots & \cdots & 1 \end{bmatrix} \tag{10}$$

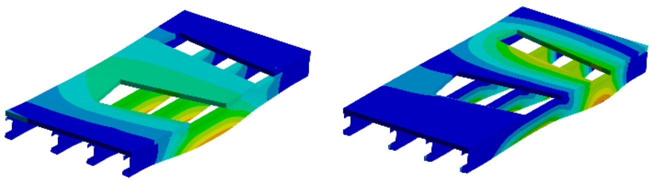
P_{ei} from (6) can also be interpreted as the local acoustic intensity and can be expressed from the radiation resistance matrix as (11).

$$P_{ei}(\omega) = v_{ei}^* ([R]\{v_e\})_i \tag{11}$$

III. RESULTS AND DISCUSSIONS

A. *Vibration results*

Free vibration analysis is performed to retrieve the vibration mode shapes and natural frequencies according to (1). Fig. 4 shows the two modes with the highest participation factor in vertical direction (Z) for the configuration with PET foam as core material and isolation pads. Natural frequencies of these modes are primarily governed by the masses of the additional structures. They are not sensitive to core material or the presence or absence of isolation pads. Heavy added structures induce bending vibrations on the support beams. Since floor slab and beams are coupled through bolted connections, vibration is transmitted near the cutout region in Fig. 4.



(a) – Mode 1: 56 Hz (b) – Mode 8: 120 Hz

Figure 4. Floor slab free vibration.

B. *Acoustic radiated power*

The structure depicted in Fig. 3 is subjected to harmonic acceleration amplitude of $0.25g$ at the fixed supports location. The radiated sound power calculated using equation (9) is shown in Fig. 5 for two different core materials with and without isolation pads. At very low frequencies, the first two most prominent peaks are attributed to the vibration of the additional structures. Fig. 6.a illustrates the acoustic intensity calculated using equation (11), at $56\ Hz$, which corresponds to the first resonance led by the added structure 1 (Fig. 3). The position of the support beams and cutout location have an impact on vibration and sound radiated power. It is essential to control the vibration in this frequency range to prevent damage to the system's integrity and fatigue failure.

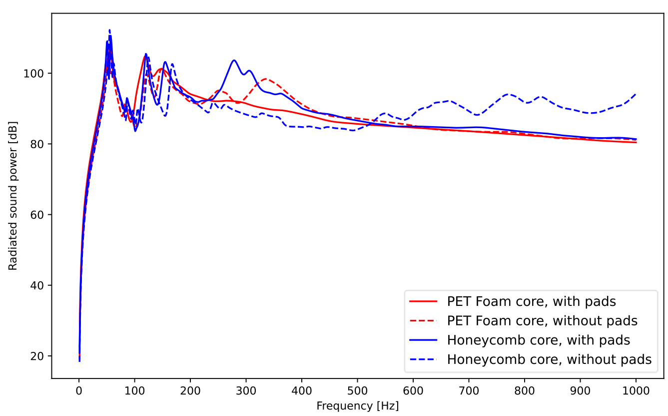


Figure 5. Radiated sound power for different scenarios.

However, for auditory perception and noise issues, radiated sound power at higher frequencies must be compared. For frequencies greater than $500\ Hz$, Fig. 5 shows that radiated sound power increases for configuration with honeycomb core material and without isolation pads. At higher frequencies, isolation pads are used to dissipate energy from vibrations whose wavelength is shorter than the distance between bolts. Fig. 5 also demonstrates that the PET foam core reduces radiated sound power without isolation pads. This is due to the increase in inherent damping of the floor slab. Therefore, the core material of sandwich structure must be carefully selected. Floor slab with PET foam core has same performance as honeycomb core with isolation pads, saving money and installation time. Furthermore, PET foam core has a lower environmental impact compared to the metal honeycomb [5]. The multidisciplinary method enables the comparison of such different aspects simultaneously, guiding the design of the mechanical structure and providing a comprehensive approach to structural optimization.

Fig. 6.b illustrates the floor region at the origin of the sound radiation peak at $278\ Hz$ when pads and honeycomb core material are considered. This peak is due to a lack of fixtures, deliberately removed for this study in this corner. In contrast, Fig. 5 shows that the use of PET foam core suppresses this peak. The developed vibroacoustic approach enables the identification of critical zones in the structure, allowing the prevention of noise issues.

Fig. 5 shows that sound radiation power increases between $200\ Hz$ and $400\ Hz$ for design without isolation pads and with PET foam core material. This is due to bending vibration of the floor slab between the support beams. Fig. 6.c presents acoustic intensity at $334\ Hz$ where bending regions are clearly visible. With the removal of isolation pads, those peaks appear whatever the choice of material for the floor. However, PET foam core decreases stiffness of the slab and shifts those peaks to lower frequencies. The ability to control the frequency range of those peaks is important as the perception of noise will vary significantly. Human beings are more sensitive to and bothered by high-frequency radiation.

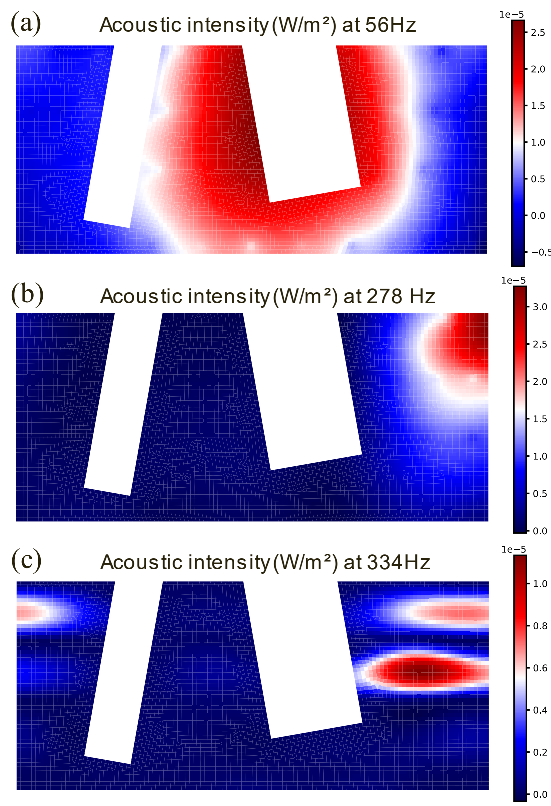


Figure 6. Acoustic intensity over the floor slab. (a) PET foam core with pads. (b) Honeycomb core with pads. (c) PET foam core without pads.

IV. Conclusion

A multidisciplinary method for simulation guided design has been developed using Python programming language. CAD scripting is used to automate the geometric design. Packages of commercial finite element software offer the possibility to automate model in Python code without interacting with the user interface. FEM is used to get vibration performance and verify structural requirements. The elementary radiator method is implemented to calculate the radiated sound power of a floor slab from a forced response of the structure. With a full parametrization of the structure, the approach is used to compare various scenarios on different aspects (structural, vibroacoustic, and environmental). Design parameters can be the material, the geometry or the technology choices as discussed for isolation pads. The method allows quick sensitivity analysis of parameters as well as the modification of multiple parameters at once. The simulation-aided design does not yield exact results, but guidance based on the relative behavior of different scenarios definitely reduces the physical design iterations and improves the efficiency of the overall design process. Another advantage of the developed design frame is that it is entirely based on Python, and thus it can be easily combined with optimization algorithms to improve the design. Once the finite element model and analyses automated behind a user-friendly interface, the design tool can be used by non-experts in simulation.

The developed general simulation-driven mechanical design approach is implemented on floor slab of an aircraft simulator using vibroacoustic simulations. It is shown that the first modes of vibration are related directly to the mass of the additional structures. Based on forced vibration response, results show that radiated sound power at higher frequencies can be reduced by choosing core material with high inherent damping for the sandwich floor slab. The results also demonstrate that many geometric parameters affect vibroacoustic performance: locations of cutout, beam supports, bolts and isolation pads.

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