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Metamaterial-Based Passive Noise Control for the Piaggio P.180 Cabin

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ABSTRACT
This work investigates the potential of acoustic metamaterials to outperform a conventional sound insulation package on the Piaggio P.180 aircraft, in terms of vibroacoustic attenuation at the blade pass frequency (BPF) and its harmonics, under strict constraints on mass and available installation volume. The approach integrates analytical metamaterial design and sizing, impedance extraction, and fully coupled structural-acoustic simulations of the aircraft, using a high-fidelity P.180 finite element (FE) model. Propeller tonal excitation is computed by computational fluid dynamics (CFD) simulations at cruise, mapped onto the aircraft FE mesh and solved by MSC Nastran. The metamaterial treatment is represented through its impedance, introduced as an acoustic boundary condition, applied to frequency-dependent fluid acoustic absorber element adjacent to cabin skin surfaces. Metamaterials performance, in terms of cabin sound pressure level, is benchmarked against the conventional insulation package.
Keywords: Cabin noise; turboprop; blade pass frequency; acoustic metamaterials; impedance boundary condition; MSC Nastran.

MOTIVATION AND CONTEXT
Enhancing aircraft efficiency and safety remains a priority for manufacturers, while passenger comfort has gained equal relevance in a competitive aviation market. Cabin comfort substantially shapes passengers' overall experience and influences airline preferences. Positive comfort perceptions can increase the likelihood of selecting the same aircraft or airline again [1]. Among comfort drivers, noise, vibration, and harshness (NVH) plays a central role because prolonged exposure to elevated tonal and broadband noise can lead to annoyance and dissatisfaction.
From a physical standpoint, cabin noise results from complex vibroacoustic interactions between elastic structures and surrounding fluids, characterized by mutual coupling between structural vibration and acoustic pressure fields [2,3]. These interactions are governed by geometry, boundary conditions, material properties, and frequency-dependent excitation, and may involve resonance and energy dissipation mechanisms. Consequently, high-fidelity numerical approaches such as the finite element method (FEM), often complemented by other deterministic or hybrid strategies, are typically required to predict and mitigate cabin noise [4–6].
Turboprop cabins pose specific challenge, in particular, tonal components at the propeller blade pass frequency and its harmonics can dominate perceived annoyance, while long wavelengths at low frequency make passive insulation packages thick and heavy. Traditional solutions can be effective but may conflict with stringent mass and packaging constraints, particularly when targeting the first BPF. This motivates the exploration of acoustic metamaterials, engineered subwavelength structures that can exhibit tailored effective impedance or enhanced absorption around target frequencies, as candidates for lightweight, compact passive control of tonal cabin noise.

MATERIALS AND METHODS
This study exploits a comprehensive coupled structural-acoustic FEM model of the Piaggio P.180 passenger cabin [7]. The model adopts a hybrid discretization strategy (three-dimensional fluid elements for the cabin volume, shell elements for skins/panels and one-dimensional elements for stiffeners and reinforcements) to capture the structural complexity needed for low- and mid- frequency response prediction. Starting from a baseline white body fuselage, internal structural components and relevant connections were added to enable realistic transmission path, supporting localized as well as global assessments of cabin noise and vibration.
In the present work, the FE model is employed as the simulation backbone for evaluating passive treatments. This ensures that any performance difference between a metamaterial sandwich structure and a conventional one is attributed primarily to treatment physics and integration strategy, rather than to changes in the aircraft-level numerical representation.
The objective is to quantify the noise reduction improvement by replacing a conventional passive sound insulation package with a metamaterial-based treatment on the P.180 fuselage, focusing on the propellers BPF and its harmonics, under cruise operating conditions. The comparison is conducted at aircraft level and includes cabin sound pressure level (SPL) reduction, as well as areal mass and thickness/space occupancy versus the

conventional package.
Metamaterials comprise periodic unit cells that exhibit resonance-driven effective properties over targeted bands. When coupled to a host plate, stepped or lumped resonators can precisely control and manipulate sound waves through specific geometric configurations, arrangements, and material combinations, improving sound transmission loss (STL) in the targeted region.
An analytical model [8,9] is used to set the unit-cell resonator parameters (mass, stiffness, damping, and geometric descriptors) that satisfy aircraft constraints (areal mass and thickness) while targeting the BPF and its harmonics. The analytical model is based on an impedance approach for plate sound transmission. In this framework, STL behavior is interpreted through the relationship between the plate's dynamic impedance and the acoustic loading. Locally resonant attachments modify the effective impedance of the host structure, producing resonance and antiresonance features that can either enhance or degrade STL.
Propeller noise at cruise is computed by CFD and post-processed to obtain the complex acoustic pressure field associated with the first BPF and its harmonics. The resulting pressure distribution is interpolated onto the aircraft FE mesh. This mapping preserves both amplitude and phase information, which is essential for accurate tonal response prediction and for capturing interference patterns and structural-acoustic coupling effects.
To this purpose, DAREA and DPHASE Nastran cards will be used to properly allocate the forces while preserving both amplitude and phase information. The fully coupled analysis is automatically set up through inclusion of the ACMODL card within the Nastran bulk data input file. A direct frequency response solution is then performed on the coupled structural-acoustic model to compute the cabin pressure response at the tone.
For the benchmark configuration, the baseline P.180 equipped with a conventional sound insulation package is investigated by using the same impedance modelling approach.
Beyond performance comparison, this paper provides a practical toolchain that starts from the analytical metamaterial synthesis, proceeds through impedance identification in a standardized numerical setting, and ends with a full aircraft vibroacoustic assessment under simulated tonal loading. This enables systematic exploration of trade-offs among attenuation, mass, and thickness, supporting the development of next generation passive cabin noise control solutions for turboprop aircraft.

CONCLUSIONS
This work proposes a comprehensive methodology to assess metamaterial-based passive noise treatments on the Piaggio P.180, targeting the first propeller BPF and its harmonics. The method integrates constrained analytical design, frequency-dependent numerical impedance extraction, and fully coupled aircraft structural-acoustic simulations, driven by CFD-derived tonal excitation. Performance is benchmarked against a conventional insulation package in terms of cabin sound pressure level reduction, mass and packaging constraints.

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Primary author: Ms BRANCACCIO, Carmen (Università degli Studi di Salerno)

Co-authors: Mrs PALMIERO, Felicia (Piaggio Aerospace); Mr TRAVOSTINO, Giorgio (Piaggio Aerospace); FASULO, Giovanni (Università degli Studi di Salerno); Dr BARBARINO, Mattia (Italian Aerospace Research Centre (CIRA)); CITARELLA, Roberto (Università degli Studi di Salerno)

Presenters: Ms BRANCACCIO, Carmen (Università degli Studi di Salerno); FASULO, Giovanni (Università degli Studi di Salerno)

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