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Acoustic Comfort Evaluation in the Passenger Cabin and Cockpit Through a Mixed-Reality Environment

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Abstract This work develops a method for converting the results of vibroacoustic numerical simulations into virtual perceived noise. The goal is to evaluate solutions for reducing noise in passenger cabins in virtual mock-ups using a user-centred approach. Passengers wearing augmented reality headsets are immersed in the cabin environment, both visually and auditorily. This article describes the virtual auralisation process and presents a case study of a business jet cabin to evaluate the quality of the developed method.

Introduction

The acoustic footprint of an aircraft not only affects the structure through vibrations, but also plays a key role in the flight experience in the passenger cabin and the cockpit. In the former, the problem mainly concerns user comfort [1], although novel aircraft configurations could bring noise levels above the recommended thresholds; in the latter, in addition to the comfort problem, excessive noise levels could compromise pilot performance and increase pilot workload. For these reasons, users should take a central role in assessing interior noise for new aircraft configurations or evaluating the effectiveness of new acoustic solutions. Nevertheless, noise impact assessment has been conventionally carried out using human-based metrics, i.e. comparing measured noise levels with parameters derived from physical and physiological laws and data from experience. While this assessment method can be valid for regulatory compliance, it fails to assess qualitatively the impact of noise variation on users. To make a qualitative and reliable evaluation of the effect of an acoustic variation on passengers and crew, users need to be directly involved in the design and evaluation process, thus using a human-centred approach. Studies have already been carried out in the comfort assessment field utilising this type of approach [2]. In particular, the evaluation must pass through the “immersion” of the user in the environment by constructing a mock-up. Given the complexity of creating an aircraft cabin and considering the acoustic aspect, it is preferable to use virtual mock-ups, which guarantee less time and cost and greater flexibility in trying out different designs and acoustic solutions [3, 4]. This aspect proves essential in preliminary design phases. The present work aims to define a human-centred approach for assessing interior noise in the passenger cabin and cockpit [5, 6]. The origin of the noise, or instead of its variation, can be manifold; in this study, we focus on a decrease given by applying acoustic metamaterials capable of absorbing certain frequency bands. Given the acoustic footprint of the aircraft, the aim is to construct a virtual mock-up containing both the visual layer (what the user sees), defined by the cabin design, and the auditory layer (what the user hears). The former is conventionally called visualisation; similarly, the latter is called auralisation [7]. In addition, to increase the realism of the experience by incorpoating the inertial effects of flight, and

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to avoid having to virtualise the cockpit due to the complexity of both design and gestures, the virtual environment is implemented within a full-motion flight simulator, in which both the cockpit and a section of the passenger cabin are present. The core objective is to import the numerical results into the virtual environment and then deploy the virtual environment in head-mounted display [8, 9]. The integration of the simulation data is achieved by condensing some of the numerical data issues, i.e. acoustic pressures as a function of frequency and position in the aircraft:

- The results are in the frequency domain and therefore need to be returned to the time domain with the inverse of the Fourier transform and then converted to an audible audio format.
- Some simplifications are made in numerical simulation, particularly on sound sources and frequency range. This compromises the realism of the generated audio files, which are thus used as filters applied to a baseline noise to avoid having an unrealistic audio track or one with anomalous sound levels. This process is possible by knowing the actual tracks of the aircraft or, in general, of the most relevant sources (e.g. the engine).

The primary objective of this work is to validate the methodology and feasibility of the cabin virtualisation process, focusing on the realism of both visual and aural components. A secondary goal is to assess the effectiveness of the implemented soundproofing solutions in a preliminary manner. The final design was deployed on a Microsoft™ HoloLens 2 Augmented Reality (AR) device, chosen for its 3D rendering capabilities, world-locking features, and integrated spatial audio system. The cabin layout was designed as a CAD model and imported into Unity, where it was refined using a scanned 3D model of cabin section represented in the full-motion aircraft simulator at Enna Kore University.

Auralisation process.

The auralisation workflow consists of three stages:

- The aircraft's acoustic footprint is obtained through numerical analyses estimating cabin sound pressure distributions across frequency, used to evaluate soundproofing materials.
- Simulation results are processed to obtain impulsive responses in the time domain (IRs), thus convolved with the dry sound of an aircraft engine, generating convolved sounds, which are integrated into the virtual aircraft model.
- Participants experience both visual and acoustic stimuli representative of a cruise flight phase in an immersive virtual environment, enabling subjective assessment of realism and comfort.

Vibroacoustic analysis is performed over a representative half-section of the aircraft cabin, corresponding to the flight simulator at the Enna Kore University. The vibroacoustic model is reduced to a half longitudinal section for symmetry optimisation. The cabin walls are modelled as an external 3 mm-thick aluminium panel (equivalent to the thickness of a real panel plus ribs and frames), jointed with an internal 24 mm soundproofing panel. Two solutions are compared, using Nomex and an acoustic metamaterial as the soundproofing material of the panels of the cabin. To simulate an impulsive analysis, the simulation utilises a point source emitting modal frequency sound (one frequency at a time) over a range of 20 Hz to 1000 Hz, with a constant step size of 5 Hz up to 500 Hz and of 20 Hz up to 1000 Hz. The source is positioned externally to the cabin, at a location equivalent to the engine position on the real aircraft. Probes placed at key cabin locations record complex acoustic pressure values at each location, representative of the transfer function of the cabin footprint. The analyses are performed based on the data in for the metamaterial, panels of melamine foam with cylindrical inclusions of aluminum, that was already tested in a fuselage environment in [10, 11]. The metamaterial is developed to absorb low-frequency noise, and for this reason, FEM is chosen as the numerical solution and COMSOL Multiphysics® as software. Once

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the analysis is performed for both materials, these frequency-domain data are then converted into time-domain IRs via inverse real FFT to enable audio convolution. The data are interpolated on a uniform grid, smoothed to highlight the overall transmission characteristics, and band-limited to 14 kHz. A global normalisation is applied across the two analyses to prevent clipping in the final audio files, ensuring consistency between Nomex and metamaterial measurements and retaining the respective soundproofing capacities. The resulting IRs are exported as 48 kHz WAV files and convolved with a dry source signal toobtain simulated audio outputs:

$$y(t) = s(t) \cdot h(t) \quad (1)$$

The two convolved sound sets (Nomex and metamaterial) are further refined for seamless looping and prepared for integration.

The processed sounds are integrated into Unity to create a coherent audio-visual experience. Probe positions from the vibroacoustic model are used to position corresponding sound sources in Unity as shown in Fig. 1. Each probe features two audio sources reproducing the Nomex or metamaterial convolved sound obtained for that location, respectively. Each set of sounds relates to a specific audio group in the sound mixer. Application commands enable toggling among the two audio groups at runtime, allowing the user to hear the different sound presets for each solution, one at a time. The cabin geometry is that of a business jet, developed as part of the European CASTLE (CAbin Systems design Toward passenger welLbEing) project. Only a section with three seats and other design elements is used.

The active audio group's volume distribution is controlled through Gaussian interpolation based on the user's (camera) position relative to each probe. Each probe contributes proportionally to the total perceived sound according to its distance from the user. A global normalisation ensures that the sum of all source volumes equals unity, reflecting the fact that the probes represent measurement points inside the cabin, rather than physical sound emitters, thus no distance-based absolute attenuation is applied. Since point sources are used, the sound is rendered in the entire cabin.

The final application is deployed on HoloLens 2 and spatially aligned with an equivalent simulator for testing, ensuring the virtual seats are positioned in alignment with their real-world counterparts.

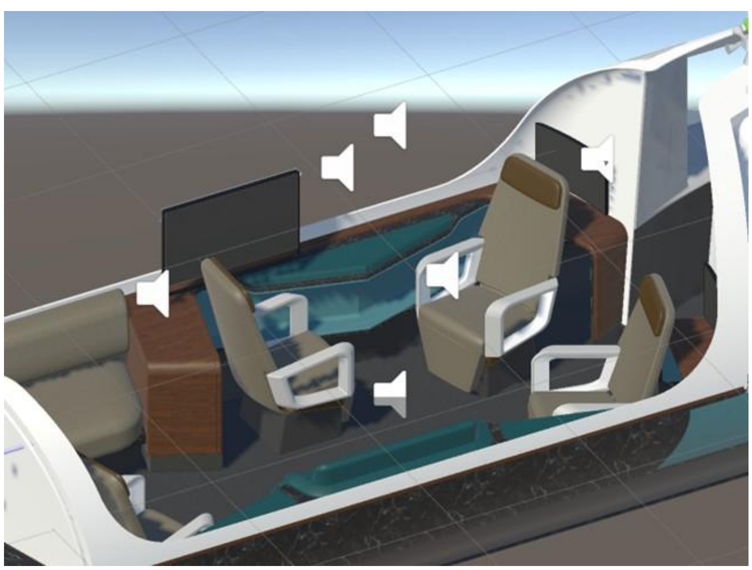


Figure 1: Unity model, with an array of six sound sources, corresponding to the probes of the vibroacoustic analysis, surrounding the cabin section used for the test.

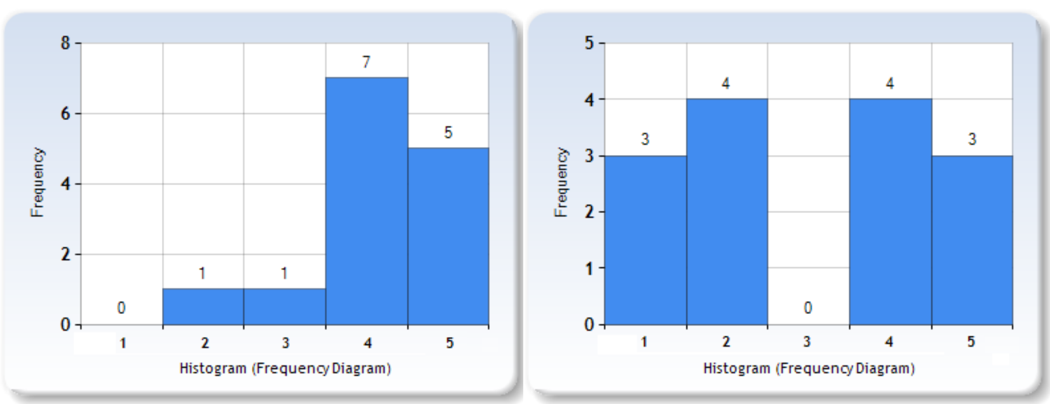
User Testing Experiment Design.
The user testing phase evaluates the realism of the virtualised cabin and user perception of acoustic treatments. A within-subjects design is adopted, where each participant experiences both the Nomex and one of the two available metamaterial conditions, with the order of presentation of the solution changed between participants to minimise habituation effects. Each participant completes two sessions, one for each of the two presented conditions: first, seated for two minutes, and then walking through the virtual cabin for two minutes. After both sessions, users complete Likert-scale (from 1 to 5) questionnaires to assess the perceived realism of the visual and aural layers, as well as the differences between acoustic configurations.

The questions and answers for each participant are reported in the Tab. 1, along with their mean value.

The realism of the scenarios is satisfying, with a mean value above 4 and low standard deviation below 1. Participants are also able to perceive the difference in sound between the two scenarios, as reported in Fig. 2(a). This difference is expressed in a decrease in low-frequency noise. The main problem lies in understanding which of the noises is louder, with about half of the participants incorrectly assigning the difference in noise, Fig. 2(b). The results give a perfect average of 3 and a standard deviation of 1.57. The reasons for this can be found in the exposure time which is very short.

Table 1: Results of the questionnaires, using Likert-scale where 1 is the minimum (Strongly disagree) and 5 the maximum (Strongly agree). The first scenario, panel in Nomex, is the louder than the second, panel in metamaterial.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Mean**
The business jet cabin is realistic	4	4	4	5	4	5	5	5	3	5	4	4	5	5	4.43
The sound faithfully reproduces that of a real airplane.	3	4	5	5	4	3	5	5	5	4	3	4	5	4	4.21
When moving around the cabin, the sound/noise is smooth and realistic.	4	4	5	5	5	4	4	5	5	4	5	4	5	4	4.50
The two scenarios have different noise levels.	4	2	4	4	5	3	4	5	5	4	5	4	5	4	4.14
In the first scenario, the noise is louder than in the second.	5	2	2	2	5	1	4	1	5	2	4	4	1	4	3.00



(a) (b)

Figure 2: The results for the last two questions in Tab. 1. (a) The two scenarios have different noise levels. (b) In the first scenario, the noise is louder than in the second.

Conclusions

The method presented starts from a numerical simulation and basic audio to recreate internal noise through signal convolution. The results show that the noise is realistic, but future experimental campaigns are needed to test its use in assessing acoustic comfort.

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