DESIGN AND DEVELOPMENT OF THE VISUAL AND AUDITORY LAYER FOR DIFFERENT CABIN/COCKPIT LAYOUT

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Abstract

This study, part of the Italian PRIN project TWINCRAFT - Digital Twin for Human-Centred Design of Future Aircraft, explores the enhancement of acoustic comfort for passengers and pilots through noise reduction in aircraft using advanced acoustic metamaterials. We assess comfort via a human-centered design approach, integrating noise auralization in eXtended Reality (XR) within the passenger cabin. This novel method utilizes augmented and virtual reality technologies alongside physical flight simulators to evaluate the efficacy of noise reduction strategies. The acoustic field, i.e., noise, calculated using accurate numerical analyses, is integrated into a digital mock-up of an aircraft through auralization. In this way, by combining the auditory layer and visual layer defined in previous works, it is possible to create an immersive experience for the user. The paper details the auralization process, from vibro-acoustic analysis of a section of an aircraft fuselage to the creation of an acoustic digital twin, thereby optimizing the aircraft design process.

Keywords: Auralization, Aircraft noise, Extended reality, Cabin design

1. Introduction

Passenger and crew comfort inside the aircraft cabin and cockpit is becoming a crucial factor in modern aircraft design. Customer requirements are a key motivation in business and design [1]. This suggests that the increase in comfort cannot only attract more passengers, but also contribute to the financial growth of airlines [2]. Comfort, in this context, encompasses the flight quality and the aircraft cabin's design. Cabin comfort design involves many issues, including aesthetics, space, safety, service efficiency, and physical aspects (sound and vibration transmission, heating and air conditioning, ventilation, lighting, and other ergonomic elements).

The factors that affect the comfort level in an aircraft cabin include visual comfort, interaction comfort (usability, ergonomics such as reachability, accessibility, and visibility), postural comfort (including postural angle, sitting pressure distribution, surfaces of contact), living space comfort, acoustic comfort, and thermal comfort. Visual comfort and interaction comfort are usually studied in cabin interior design, in particular referring to seats and aisles or the cockpit for the pilots [3, 4, 5]. Visual comfort depends on the sense of sight and includes the look of the cabin interior and the illuminations [6]. Moreover, thermal comfort and air quality, regulated by the air pressurisation and conditioning system, must be considered [7]. In this work, we principally consider acoustic comfort as an essential factor. Only in the last few decades noise reduction in the cabin has become a necessary requirement, leading to the realisation of future regulations and objectives at a global level [8, 9]. Noise has several adverse effects on people, caused by a one-time exposure to an intense impulse sound or by steady-state long-term exposure to a sound pressure level higher than 75-85 dBA, the average noise level in a turbofan aircraft cabin [9]. Moreover, the noise also affects thermal comfort and perception, as reported in the work by Bourikas et al. [10]. Finally, comfort, and in particular aspects related to noise levels, can also negatively affect the pilot's performance due to increased fatigue. To highlight

the importance of the topic in the safety framework, it must be emphasised that the Human Factor (HF) represents one of the leading causes of accidents across all transport modes [11].
The main problem in the design process when dealing with comfort is its assessment because a flexible design method is necessary, and not all parameters have been defined yet. Generally, comfort is studied on existing aircraft or in physical mock-ups to find the main issues for further design or cabin interior improvement. This research is usually done through questionnaires to develop an assessment identifying dissatisfaction indicators of cabin comfort [12, 13]. The development of a physical mock-up is generally done in late design phases before production, limiting the flexibility and iterations of the entire design process. On the other hand, surveys on existing aircraft can only lead to minimal changes and benefits and will primarily affect the design of the new passenger's cabin.
In the design phase, comfort evaluation can follow two different paths to measure it [14]. A human model-based measurement considers the human as a model, which generally has some maximum, minimum, and average parameters. These can be obtained from physical and physiological laws (e.g., the passenger's size for ergonomics or the maximum loud noise) or a statistical survey and empirical studies proposed to the users (the passengers, the crew, and the pilots). The advantage of this approach is its simplicity. Although these parameters do not consider subjective measurements and cannot capture the user's perception in terms of emotions, it is essential to have a human-centred design process to improve comfort. This is possible through a cabin or interior mock-up, where the user experience is evaluated with questionnaires and surveys using psychometric scales. The main issue in the preliminary design phases is the availability of extensive and detailed mock-ups. Nevertheless, new technologies such as virtual and augmented reality can create virtual mock-ups (Figure 1) more flexibly and cheaper than physical one, allowing the user to switch and submit several design concepts and possible improvements [15, 16]. In previous studies, virtual mock-ups were used to evaluate visual comfort and ergonomics as in De Crescenzio et al. [15] and the crew service in Fuchs et al. [17].

Figure 1 – A virtual reality model for cabin design in [16].

Human-based models to evaluate the effects of noise on comfort levels are the A, B, C, and D filters applied to the acoustic pressure to consider the human's ear sensibility to different frequencies; moreover, usually, noise is measured in significant positions occupied by passengers; finally, the maximum comfortable or dangerous value of noise is known. All these measurements and, in general, parameters are called human-based factors. The users are not at the centre of the design process but are only considered through human-based parameters, regulations, and general knowledge. The target in aircraft and cabin design is to include users in the design process. This work proposes a design for human involvement in the loop process of the acoustic comfort assessment.
Traditional tools exploited when dealing with noise or, more generally, for comfort evaluation to study the user's direct response to comfort innovations are the physical mock-ups. The main disadvantage of this solution is the cost linked to the low flexibility of the tool: changing different interior designs or even different cabin configurations is time-consuming and expensive. This situation is compounded if the mock-up has the noise integrated into the physical cabin through loudspeakers or other acoustic sources, i.e., the physical auralization process [18, 19, 20]. XR (eXtended Reality) tools can en-

hance the human-centred design, removing the physical mock-up limitations [21, 22]. Their validity has already been demonstrated when studying ergonomics, aesthetics, and visibility in the cabin. In the acoustic field, it is possible to develop a virtual model with an auralization process like the physical one. The idea is to introduce or integrate a spatial sound in the VR/AR environment [23]. Therefore, it will be possible to improve user engagement and confidence by providing realism to the virtual environment. Thus, the user will provide a full range of subjective measurements from the virtual coupling of visual and acoustic experiences. Several noise reduction solutions can be evaluated regarding visual and acoustic comfort through auditory experiments [24] with a human-centred approach.

In this research, part of the Italian-funded PRIN (*Progetti di Rilevante Interesse Nazionale*) project TWINCRAFT - Digital Twin for Human-Centered Design of Future Aircraft, we aim to evaluate comfort enhancement due to noise reduction inside an aircraft for passengers and pilots, using cutting-edge acoustic metamaterials. Our focus is on the acoustic comfort assessment phase employing a human-centred design based on the auralization in XR of the noise footprint inside the passenger cabin. The human-centred design concept of the project, a novel approach, is reported in Figure 2. We leverage augmented or virtual reality technologies and physical flight simulators to evaluate the efficiency of the noise reduction solution. In this paper, we present the noise auralization process and development from numerical simulations to create a digital twin of the aircraft in acoustic terms to enhance the design process.

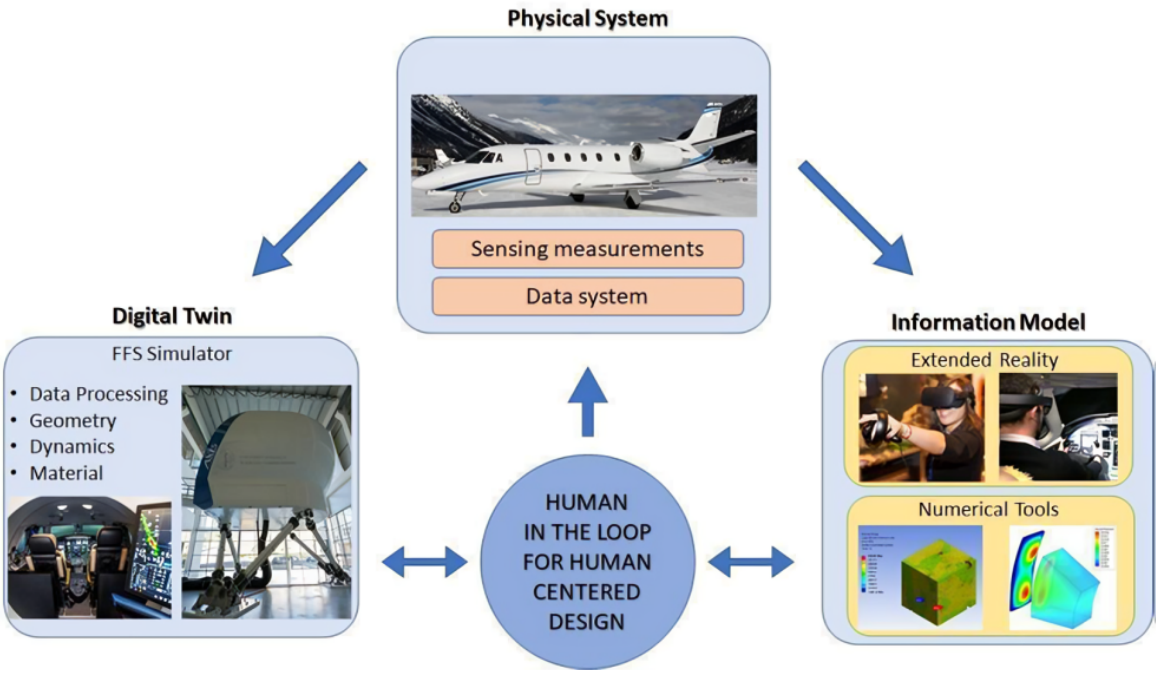

Figure 2 – Digital twins for human-centred design.

2. Auralization in a virtual environment

The aim of this proposal is thus to accomplish a high-fidelity virtualisation of both the visual and acoustic characteristics of an aircraft cabin, allowing the assessment of a well-defined procedure for the design of a digital twin of an aircraft interior based on high-fidelity vibro-acoustic analysis of cabin noise and cabin acoustic and configuration optimisation for passengers' comfort and well-being. The starting point for this work is a numerical vibro-acoustic optimisation of the cabin considering different passive noise reduction materials inserted in the fuselage panels, such as metamaterials, which have been previously characterised numerically [25, 26, 27]. Thus, this work focuses on cabin design optimisation and environment auralization, exploiting the vibro-acoustic analysis outcomes to implement three different auralization methods. These will be described in the next following paragraph to find the best trade-off between procedure complexity and feasibility of results compared to acoustic simulation results. The proposed methods will exploit the characterisation of the cabin materials and the vibro-acoustic analysis of the cabin-optimized configuration.

Focusing on a general approach of human-centred design of the cabin environment, a virtualisation process acquires great relevance in ensuring the users (i.e., flight crew and passengers) can evaluate and validate the design choices from the early stages of the development process. For the virtualisation of the aircraft cabin, modern see-through head-mounted displays have been considered the best solution in this work, with Microsoft's HoloLens 2[1] headset being capable of immersing the user in a set of scenarios spanning from a completely immersive virtual model to an augmented one superimposed on a physical cabin/cockpit mock-up environment [28, 29]. Furthermore, using mixed reality devices, the digital visual and acoustic layers can be implemented with full sound spatialisation thanks to the built-in headphones array. Digital cabin visualisation on such devices has already been accomplished in previous projects [16]. In contrast, sound spatialisation, considering the inner characteristics of the source, environment, and receiver, is realised using dedicated plug-ins compatible with the chosen Unity[2] 3D development environment and the device itself. In this case, selected software includes Virtual Acoustic for the computation of audio source configuration and properties before implementation in Unity, the Project Acoustic Unity plug-in for the characterisation of the acoustic properties of the cabin geometrical model, and the Microsoft Mixed Reality Toolkit head-related transfer function (HRTF) Spatializer plug-in, available in Unity and capable of creating source-listener related spatialisation, reconstructing sound distance and direction, also based on the user's physical characteristics (in this case, a simplified HRTF model using interpupillary distance). The different software are used together or alone to test three approaches to reproduce the typical cabin noise based on the sound characteristics reported by vibro-acoustic analysis, with a final application distributed and executed on HoloLens 2 to combine visual and aural layers in the user experience. As there is still a lack of research on the auralization of noisy environments based on vibro-acoustic analysis, comparing different approaches for sound spatialisation appears to be the best solution when the validation of the obtained results is tuned with acoustic simulation outputs. More generally, the proposed technique could fit with other environments characterised by noise and vibrations, such as cars and trains.

Starting from the visualisation layer, a three-dimensional cabin model is imported into the development environment and then deployed to the mixed reality device, considering different interior configurations, which also affect the acoustic properties of the cabin. The auralization then considers three approaches summarised in Figure 3, two of which are based on tuning the source, while the third is on tuning the acoustics of the virtual cabin:

- single source tuning;
- multiple source tuning;
- virtual model tuning.

The single source tuning considers acoustic parameters obtained from the vibro-acoustic analysis, such as sound pressure level and velocity three-dimensional maps, to get sound-describing parameters using the time and frequency domain of the acoustic response. A mesh grid of probe points defined by sound volume, sound direction, reverberation, and other relevant acoustic parameters results from the process, allowing parameter interpolation based on the user location and placing a single virtual source according to the determined acoustic properties related to that position. This method accomplishes simple sound reconstruction, which may reduce the capability to reproduce all the sound effects of physical cabins.

The multiple source tuning tries to reconstruct an array of virtual audio sources matching the acoustic field inside the cabin obtained by vibro-acoustic analyses, minimising the error in the tuning of a point-distribution of sound properties with a finite and limited number of point sources properly positioned and characterised in terms of acoustic parameters. This method seems advantageous, corresponding to a more conventional auralization process. However, it results in more complex tuning and generates sources uncorrelated with the original ones in both position and acoustic parameters.

[1] https://www.microsoft.com/it-it/hololens

[2] https://unity.com/

Other than these source-based methods, which ignore the cabin acoustic geometry, fully exploiting the results already obtained from vibro-acoustic simulations, the virtual model tuning tries to model the virtual cabin and calculate its acoustic geometrical properties. Exploiting the Microsoft Project Acoustic plug-in,[3] the acoustic properties of cabin materials (lining panels, metamaterials, etc.) characterised for vibro-acoustic analysis are used to run a full acoustic wave simulation of the modelled virtual cabin. An iterative wave simulation process is then implemented, varying the virtual material properties to match the results from the acoustic simulation wth those from vibro-acoustic analysis. The outcome is a complete set of cabin acoustic parameters computed in significant sampling positions for multiple source locations used for interpolation with the actual user position. Thus, it is possible to place the sources in their original locations and reliably evaluate operational conditions far from those assessed in the vibro-acoustic analyses, just tuning some general acoustic parameters and having real-time responses as the user moves inside the cabin. As a negative implication, matching with the vibro-acoustic map could be difficult and time-consuming, and the Project Acoustic plug-in provides limited customisation of simulation parameters, such as mesh and probe resolution.

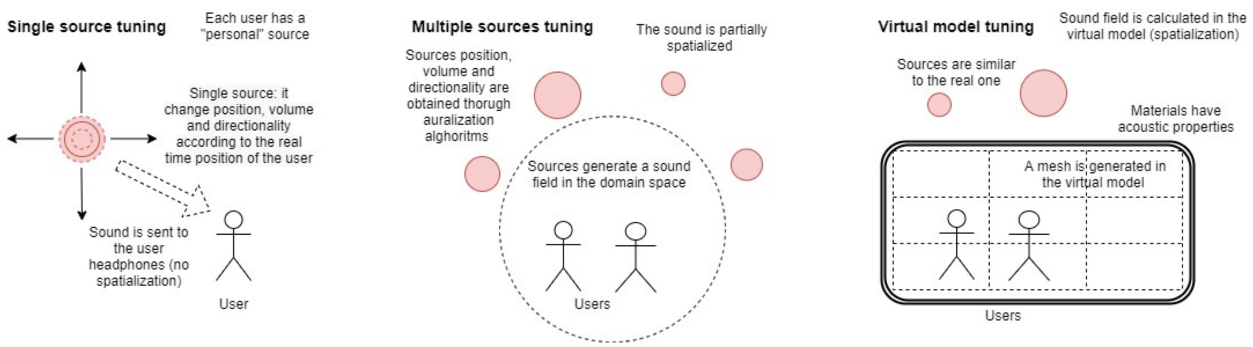

Figure 3 – Description of the three identified auralization methods.

All the methods rely on matching auralization results with vibro-acoustic maps and allow for the generation of the needed tuned sound sources to stream the audio of the engine and turbulence noise with cabin spatial reconstruction. Other sources, such as air conditioning, cabin loudspeakers, and cabin voices, can be added with a proper sound reconstruction, and a hybrid technique, joining different spatialisation methods for various sound sources, is considered, as Unity allows this approach.
With HoloLens2 visualisation and sound spatialisation capabilities, it is possible for the user to freely move along the virtual cabin, constantly having a real-time faithful reconstruction of cabin noise. This allows a proper validation of proposed acoustic and configurational solutions concerning applied passive noise reduction methods and cabin ergonomic design.

3. A conceptual model for preliminary cabin auralization

3.1 Baseline model from numerical simulation

For auralization, a simple vibro-acoustic model of a fuselage barrel, consisting of half a section on which a symmetry condition is applied, is used. The geometry and components were created in previous work by Cinefra et al. [30] to calculate the internal noise with a software based on the finite element method (FEM). To visualise and auralize the geometry, the main cavity of the passenger cabin, the two seats and the interior design elements, such as the overhead compartments, are of interest. A picture of the FEM model is shown in Figure 4. The results are obtained between 1 Hz to 500 Hz. The prominent engine and turbulent boundary layer noises are concentrated in low frequencies. In addition, low frequencies are particularly difficult to absorb with conventional structural materials and are, therefore, the area of interest for acoustic metamaterials and other noise reduction solutions. The human presence is not considered in the numerical analysis. According to Flynn et al. [31] the head shadow effect is not significant at low frequency. Because the wavelength is sufficiently long for the sound to bend over or around the head. Simulations are performed with FEM-based software.

[3]https://github.com/microsoft/ProjectAcoustics

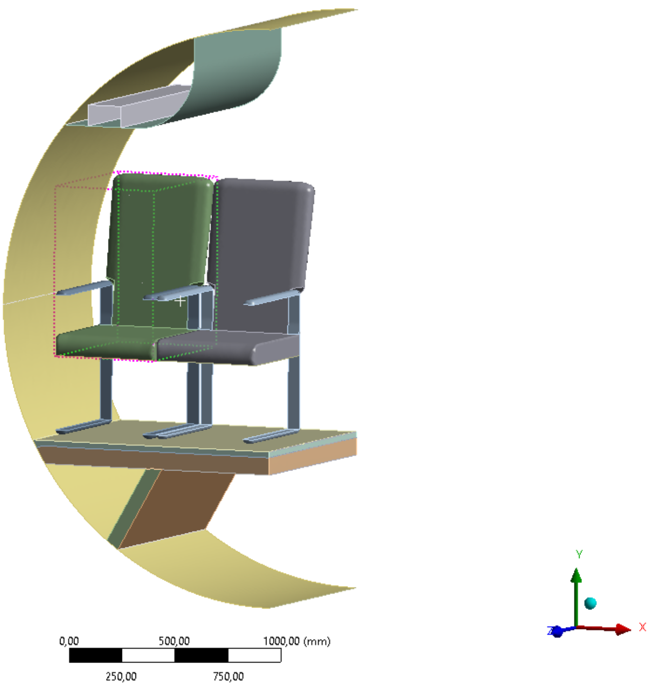

Figure 4 – The geometry of the fuselage barrel in [30].

In the fuselage environment, it is not necessary to auralize the entire cabin space but only the most significant areas, i.e., the area where the passenger's head is, considering a certain freedom of movement at the height of about 1.20 m above the floor, i.e., the average height of a seated passenger's head. However, the process can also be extended to other areas. Therefore, from the pressure map obtained with the FEM, a sub-map is extracted, as described in Section 3.2
Since the volume within the cavity on which the auralization process is to be performed is selected, the geometry in the virtual environment is generated. The results in terms of sound pressure (and, if possible, phase and amplitude) are provided, and the auralization process no longer depends on the discrete model and can therefore be applied to other FEM simulations with different geometries.

3.2 XR model

Since the visualisation layer for aircraft cabins in XR has been presented in previous research, this paper will only focus on a preliminary concept of an auralization methodology for cabin noise reproduction from the results of a vibro-acoustic analysis.
Among the three proposed auralization approaches, this study zooms in on the most promising concept identified by the authors. In this approach, vibro-acoustic data are used to calibrate specific acoustic parameters of the audio source. This method is preferred over the Project Acoustic plug-in, a game-oriented platform. According to [29], the latter often modifies or neglects specific critical audio effects to enhance the overall gaming experience, compromising the realistic reproduction of cabin noise. In contrast, using vibro-acoustic data ensures a more accurate representation of acoustic conditions within the cabin. However, as explained later, some logic behind the project's acoustic auralization process will also be exploited for this work.
This section details the model employed for the initial testing of a cabin auralization system. The digitalisation of the cabin leverages XR technologies, utilising the Microsoft HoloLens 2 see-through head-mounted display. This device facilitates the reproduction of visual and aural components, exploiting stereoscopic hologram rendering and spatial audio capabilities. The Unity Development Engine is employed to develop XR applications for the HoloLens.
The Unity project encompasses a model of a half-cabin section, which is used for vibro-acoustic analyses. A mannequin is positioned in one of the two seats to simulate the user's initial viewpoint. This mannequin serves as a visual reference to accurately position the user's camera point of view

within the XR application. Figure 5 shows the model as it appears in Unity and on the Hololens2 at runtime. The project is configured for mixed reality, integrating an anchor system to fix the model relative to the real world during runtime, along with the Windows Spatializer mixer for audio rendering on the HoloLens. The mesh used for vibro-acoustic analysis is imported into the model and aligned with the cabin section, ensuring proper coordinate conversion between FEM software and Unity. The mesh nodes are visualised within the model for reference purposes.

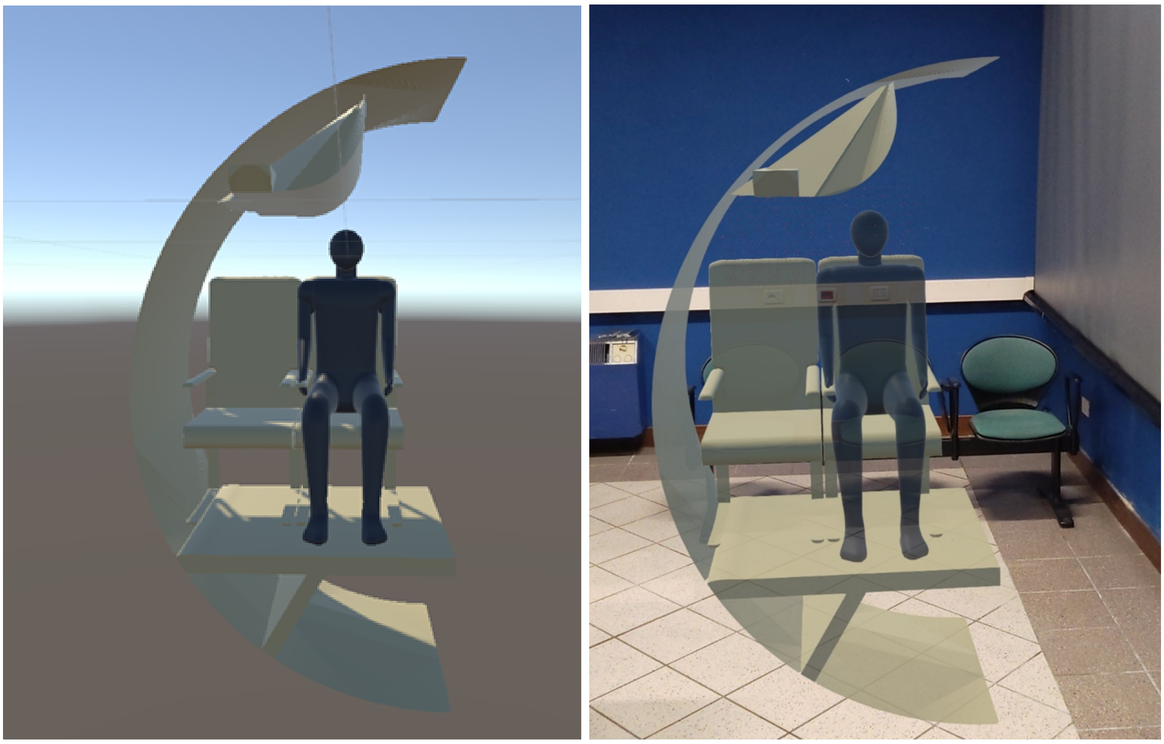

Figure 5 – Cabin model in Unity and on HoloLens at application runtime.

The nodes generated from the vibro-acoustic analysis are associated with their corresponding sound pressure level (SPL) values, thereby establishing an SPL field within the cabin, as shown in Figure 6. The application determines the user's head position within the model as it moves in the scene. It then interpolates an appropriate SPL value by employing weighted distance inverse interpolation among the four nearest mesh nodes to the user's head position. While the vibro-acoustic analysis was performed on a volume containing 4443 nodes, only 100 sparse nodes were used for the SPL interpolation, as reported in Figure 7.

This interpolated SPL value is then used in real time to modulate the volume of an external audio source, which simulates the cruising noise of a Cessna 414 turboprop engine. The audio source lacks spatial effects because the acoustic volume adjustments have already been integrated based on the vibro-acoustic analysis results. Specifically, the SPL is utilised to calculate the decibel difference relative to the cabin's average SPL, and this differential is applied as a gain factor to adjust the audio mixer volume accordingly by summation.

This preliminary auralization was finally evaluated in Unity and using HoloLens, and the alignment of the model in Figure 8 with some chairs was also assessed to let the user test the system.

4. Discussion on the preliminary model

As a critical remark, the vibro-acoustic analysis was not tuned on a realistic and accurate source of aircraft noise, as the research focus was on validating the auralization process given the data from the study.

The vibro-acoustic analysis, and hence the auralization model, was run on half of a section of an aircraft cabin containing two seats. The study was performed with some symmetry constraints on the half section. It only included a small volume surrounding the upper-body location of the two passenger seats in the model. Since the passengers usually spend most of their travel time seated, this seemed

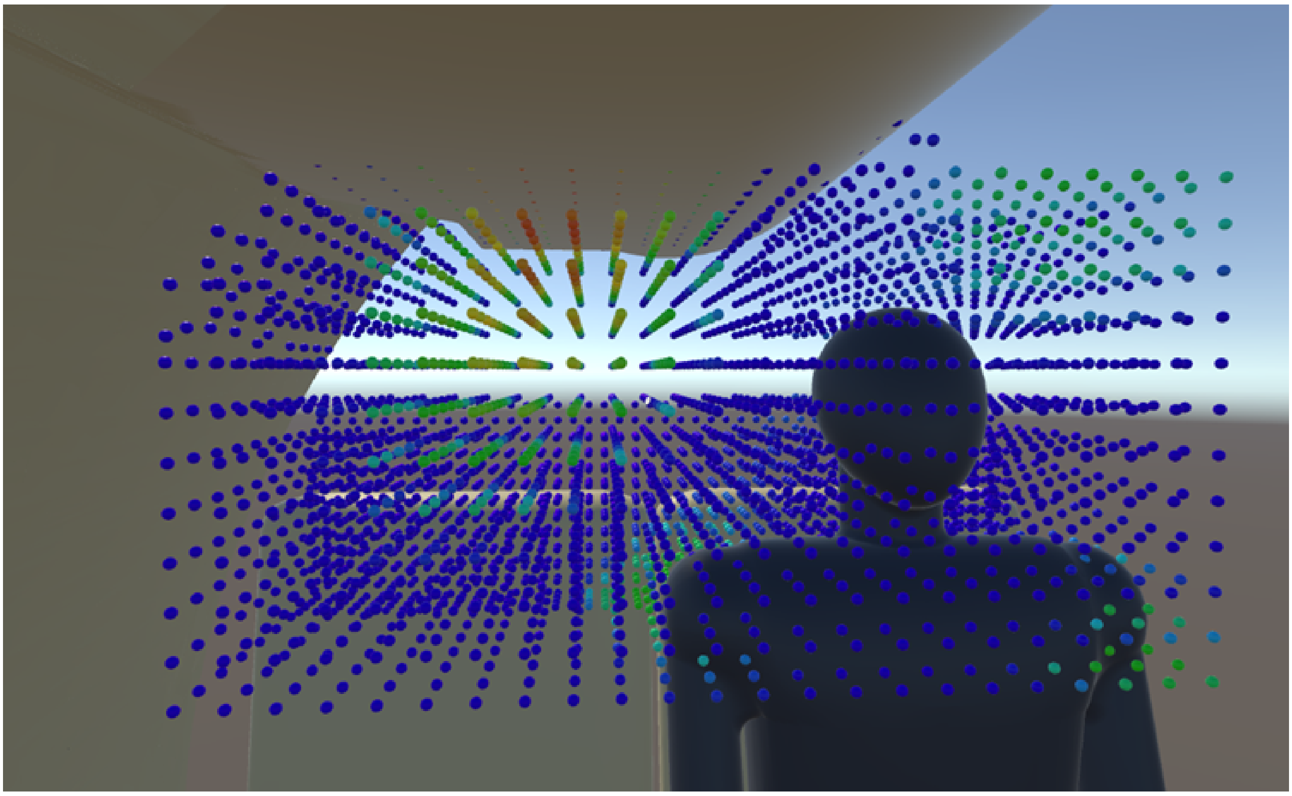

Figure 6 – The mesh model of the vibro-acoustic analysis volume, highlighting node position using spheres.

an adequate area for a first evaluation, being a convenient compromise between computational effort and possible user cases, still allowing the testing of two different positions.
Yet, the mesh points do not include all possible user position. Thus, some interpolation is needed between the values of SPL for each node. Since the proposed mesh was yet too nuanced, with more than 4000 nodes, a reduction was considered, selecting a sparse array of 100 points covering the initial volume. This was possible due to the continuous behaviour of the SPL field, shown in Figure 6 by colour mapping. This choice also considers the need for computational efficiency in future analysis of the whole cabin, considering an exponential increase in the number of nodes. Since the volume is three-dimensional, the nodes should be equally distributed for a less expensive interpolation cost. This allows for searching algorithms of the nearest nodes along three orthogonal directions, with a computation cost of $3 \cdot O(n)$ rather than $O(n^3)$. As previously stated, an inverse distance weighting algorithm is chosen for the computation of the SPL interpolated value, which is briefly described below.
The inverse distance weighting approach (inverse distance-based weighted interpolation) estimates a value v at a location $p(x,y,z)$ by a weighted mean of nearby points:

$$\hat{v}(\mathbf{p}) = \frac{\sum_1^n \omega_i p_i}{\sum_1^n \omega_i} \tag{1}$$

where

$$\omega_i = |\mathbf{p} - \mathbf{p_i}|^{-\beta} \tag{2}$$

with $\beta \geq 0$ and $|\cdot|$ being the Euclidean distance d:

$$d(a,b) := \left(\sqrt{(a_1-b_1)^2+(a_2-b_2)^2+(a_3-b_3)^2}\right)^{-\beta} \tag{3}$$

thus

$$|\mathbf{p} - \mathbf{p_i}|^{-\beta} = \left(\sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2}\right)^{-\beta} \tag{4}$$

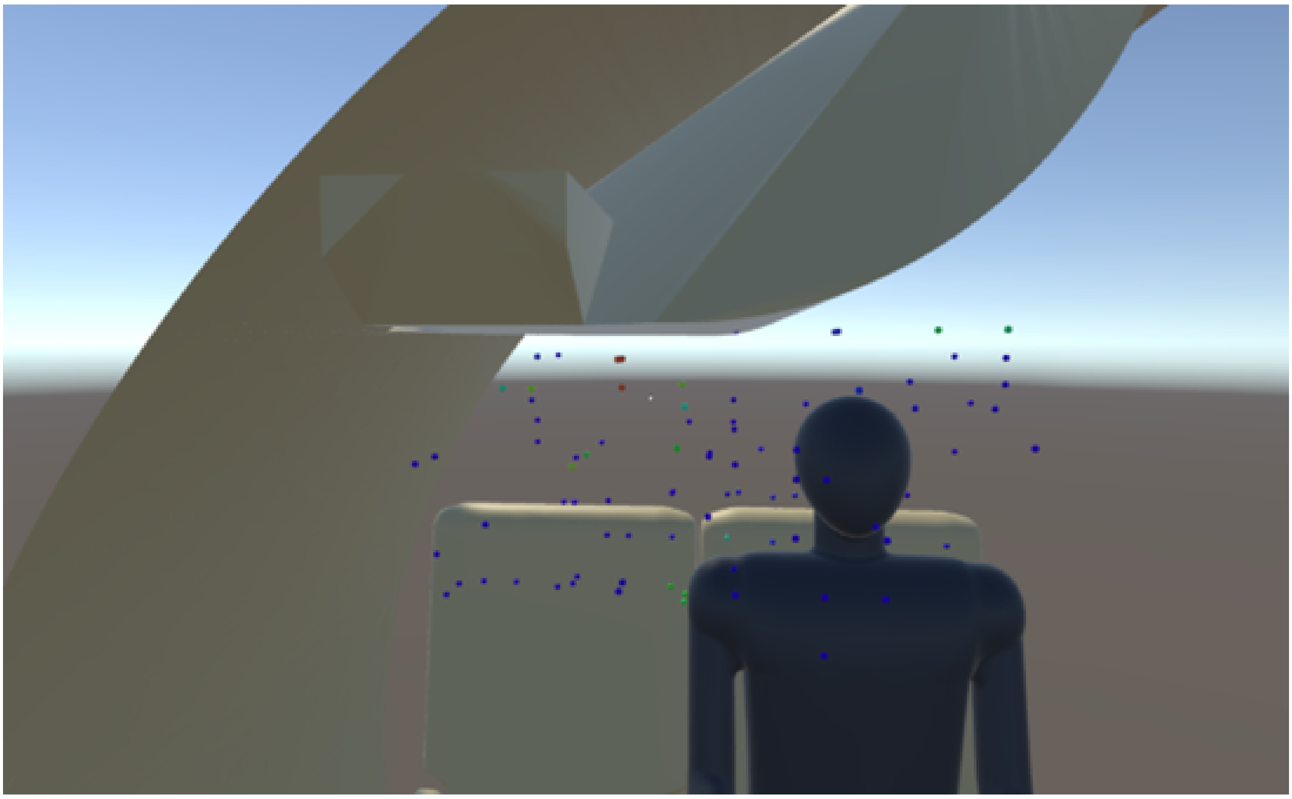

Figure 7 – Interpolation of 100 sparse nodes to reduce computational effort.

In the selected case, $n = 4$ since the original mesh has a tetrahedral structure, and each point is placed inside an element delimited by four nodes. Since the points are still close to each other, linear interpolation is considered good enough for the research aims. Thus, an inverse interpolation is chosen instead of an inverse squared interpolation, with $\beta = 1$.
Following the interpolation process, the derived sound pressure level (SPL) exhibited a notably high absolute value, a result attributed to the pressure source being active during the vibro-acoustic analysis. SPL quantifies the material behaviour within the cabin, acting as an absorber or reflector of noise. This behaviour is typically represented as a percentage of the incident energy, proportional to sound intensity, and is independent of the total incident sound intensity. Consequently, within the decibel (dB) domain, the function of a barrier to sound introduces a constant negative gain in decibels regardless of the incident source's SPL. Therefore, instead of using the absolute SPL value to set the audio source volume in the application, the difference between the SPL at a specific point and a reference value (defined as the average SPL over time and cabin volume) was employed to apply a differential gain on the audio mixer volume.

5. Conclusions

Project TWINCRAFT envisions the development of human-centred method to estimate the impact of innovative noise reduction solution on the comfort of passengers and the cabin crews. To perform this task, we employ extended reality technologies to create a digital mock-up of the aircraft. Previous solutions for the visualization layer of an aircraft cabin are combined with a novel concept for the auditory layer. Starting from three plausible auralization methods, we selected the most promising, which allows to convert a 3D acoustic pressure field from high-fidelity numerical analysis into aural source for user's experience assessment.
The initial fuselage model employed a straightforward approach by using the vibro-acoustic analysis to calculate a differential gain that linearly adjusts the volume of the engine sound source without accounting for frequency dependency. Future advancements will involve conducting an impulsive vibro-acoustic analysis of the cabin structure. This will determine the cabin's impulsive response across the entire frequency spectrum, obtained through an Inverse Fourier Transform of the cabin's frequency-domain response. The impulsive response will enable the modulation of any audio source

Figure 8 – User testing the cabin preliminary auralization in XR.

played within the cabin using a convolution product. This approach will also account for frequency and phase shifts at each node within the cabin, thereby accurately simulating sound direction.
Although the current model is less sophisticated than anticipated future implementations, it provides a foundational basis for evaluating how variations in SPL influence sound reproduction and demonstrates the potential for interpolating acoustic parameters. This initial model illustrates how data from vibro-acoustic analyses can be leveraged to enhance the fidelity of sound reproduction in a virtual environment. Furthermore, this interpolation method can be adapted for all the auralization models discussed in this study. A vital advantage of the developed model is its ability to extract acoustic parameters from general vibro-acoustic analyses instead of relying on specific audio sources. This capability facilitates the integration of different noise types and supports the inclusion of cabin characteristics with external and immutable audio sources, such as those from built-in flight simulators. Additionally, it allows for incorporating other noise sources, such as cabin acoustic signals and voices.

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8. Copyright Statement

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