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AURALIZATION OF NOISE IN A VIRTUAL REALITY AIRCRAFT CABIN FOR PASSENGER WELL BEING USING HUMAN CENTRED APPROACH

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Abstract

Noise has affected aircraft since the dawn of aviation. Aircraft noise reduces comfort for passengers and crew inside the cabin and the cockpit, in addition to the structural problem created by the vibration on the aircraft structures. Acoustic characteristics of an aircraft are traditionally represented with numerical data or are in the form of pressure maps and color maps calculated at particular positions taking into account several parameters. Audializing this data, involving potential users, is possible on physical prototypes at the end of the product development requiring considerable time and cost resources. From the past decade, innovative technologies such as Extended Reality (XR) have paved their way towards digital transformation of the products augmenting Human Centred approach. In this paper, we present a novel adaptation of these technologies in developing a multi-sensory virtual aircraft cabin environment in order to provide realism and improve immersion for a user. A new concept to “auralize” the noise inside the virtual passenger cabin, combining numerical acoustics and XR technology has been proposed to develop a tool to evaluate passenger comfort and wellbeing before the prototypes are manufactured. Different solutions on modeling acoustics in a virtual reality cabin have been studied, developed and discussed.

Keywords: Acoustics, Realism, Virtual Reality, Auralization, Multi-Sensory

1. Introduction

The noise contour in a commercial aircraft cabin plays a key role in the comfort of passengers. Several works try to define a reliable method to estimate the noise spread inside the cabin and the fuselage in order to validate new noise reduction solution [1] [2] [3]. Moreover, the development of new cabin and aircraft configuration [4] [5] require the understanding of the acoustic footprint of the aircraft, in order to define and, if necessary, reduce, the noise inside the passenger cabin and the cockpit, and the vibration, which affects the structure.

The study of noise exploits several numerical (Finite Element Method and Statistical Energy Analysis) and experimental methods. These tools have, as output, the pressure inside the passenger cabin, the vibrations on the structures or the modal shapes of several components. Therefore, the evaluation of noise usually exploits physical parameters such as sound pressure level in dB in strategical positions, the room design and passenger seats. Furthermore, in order to take into account, the different sensibilities of the human hear, the pressure in dB could be scaled exploiting some experimental filters (the A, B, C and filter) through which value of the acoustic pressure (filtered or not) is achieved on several locations in the numerical model (e.g. the nodes for a finite element method). These values are reported generally on a color scale and obtains the pressure map that describes the acoustic behavior of the aircraft for a given frequency or time step, depending on the analysis type. The maps provide acoustic engineers a lot of information on the noise in the cabin, but are usually difficult to read, due to the three-dimensional geometry of the problem (volume inside not visible). For results in the frequency domain, an engineer has to consider several maps for the same flight phase. In addition, if we consider the importance of modal shapes and vibration of the structure in the acoustic analysis (e.g. Resonance problems) it gets harder to identify the connection between numerical results and noise. From these considerations, through this work we present a novel tool to integrate numerical results from numerical simulation (or experiments) in a more intuitive way, not only for acoustic or structural researchers, but also for the other designers and researchers, who work on aircraft design.

Until now, the only way to directly study the noise reduction effectiveness from the passenger point of view is through mock-up or directly on the aircraft itself. These ways are only exploitable in the very last phases of the design and development cycle, and they are expensive and not flexible since they do not allow to explore the full range of design options in terms of configurations and noise reduction solutions.

Recent advancements in simulation technology have paved the way for new methodologies for product visualization and validation in design phase through a human-centered approach. In this context, innovative solutions such as Extended Reality (XR) technologies have already proven to be beneficial in this sector [6]. The term XR acts as an umbrella term for Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) and refers to all real and virtually combined environments. VR immerses a user in a completely digital environment whereas AR overlays digital information on to the physical world giving a semi-immersive feeling to the user. MR is an enhancement to AR allowing the digital elements to interact with the physical environment. The hardware tools for XR tech range from screen systems to hand-held devices and Head Mounted Displays (HMD). The growth of XR HMDs provides efficient, non–invasive visualization and interaction tools at an affordable cost [7]. Nevertheless, a number of simulated environments are still only half-realistic unless 3D sound effects are provided to the user. Thus, cabin noise auralization would leverage the chance of evaluating the noise solutions from a human's point of view way before the first mock-ups are manufactured. The multi-sensory modality of the immersive environment could provide the user better impression and judgement of the design. With sound effects introduced, the user will have the possibility of persistent awareness of the surroundings. The auralization can be realized importing the numerical results in terms of acoustic pressure in the virtual mockup or creating an acoustic source in the mockup and giving to the component of the model some acoustic properties. In this work, we follow the second way in order to prove the validity of the concept. The procedure will be described in the Section 3.2.

Thus, integrating an application with audio is a powerful way to improve user engagement and confidence by providing realism to the virtual environment. It adds another dimension to the user experience. Placing just an audio source at a position in VR without any effects of the surroundings does not ideally provide the user the perception of the environment. Auralization, a process of listening to an audio source as it would sound if played in a simulated and measured space is a technique to bring acoustics to Virtual Reality environments. The word "auralization" is an analogy to the word "visualization" only referring to sound instead of visuals [8]. Both visualization and auralization play a major role in evaluating a VR model through human centered approach for passenger well-being. Mismatch between the auditory cues and visual representation may result in uncomfortable perception [9]. From the past decade there are several studies ongoing on auralization for gaming applications around the world to make the games more realistic and immerse the user in a quasi-real environment. Auralization is a combination of source modelling, room acoustic modelling and receiver modelling for sound spatialization [10]. This way of creating sound in 360^0 in an immersive environment around the listener is called Spatial Sound. In general, humans can detect sound in 3 dimensions with 2 ears: in Range (distance), in direction above and below (elevation) and in front and rear as well as either side (azimuth) [11]. Developing the similar behavior through virtual reality headsets demands for methods which can characterize how an ear receives sound from a point in space. One such method used for Mixed Reality Head Mounted Displays is the Head Related Transfer Function (HRTF) technology, also known as Anatomical transfer function (ATF) [12]. HRTF is specific for each person and considers ear shape, head size and ear position to simulate sound coming from distances and direction to make holograms feel more present.

On one hand, sound designers around the world are working on simulating the audio source for accurate reproduction inside the model or the room. On the other hand, the realism of the audio experience is directly linked to the properties of the room and building the qualities to determine how sound is transmitted i.e acoustics. Acoustics is the study of mechanical wave behavior in fluid or solid media. Acoustics engineer identifies what makes noise, how it travels, what makes it quieter or louder and how people experience it from various locations. They measure and evaluate noise based on the source (what makes noise), receiver (who experiences the noise) and the path between them.

Simulating this acoustical behavior in VR rather is a complex and challenging task involving high computing costs and time. Especially, Mixed Reality systems face an enormous challenge of computational resources [13]. There are several methods and techniques such as geometrical methods, wave-based methods and hybrid methods developed in acoustics to model, simulate and measure surrounding sound fields [14]. These algorithms can provide accurate results in the form of impulse response and acoustic parameters such as reverberation time, occlusion etc. The methods have been around for a long time but compromise in accuracy and computation costs. An accurately simulated spatial room pulse response is the main reason for the quality of auralization which in turn depends on simulation method, accuracy of boundary conditions, quality of the model etc.

Geometric methods such as ray tracing method, image source method and beam tracing methods assume sound wave as a ray containing energy which are propagated in the room calculated through geometrical laws of optics. This involves high frequency approximation and several wave phenomena are lost due to the approximation [15]. Wave based methods such as finite-difference time-domain method, finite volume method etc. are solved numerically through physical wave equations. These methods usually divide a room boundary to mesh cells and solve numerical approximations on this mesh. This highlights the fact that, although it is accurate, during run-time it is computationally intensive. Finally, hybrid method is a combination of both.

Building acoustics in VR has to consider a number of factors such as source and receiver position, audio source quality, space modelling etc. Since the room impulse response is dependent on the position of source and the listener, in VR it becomes paramount to update the spatialization process with the orientation of the listener’s head. This demands the simulation of room/model acoustics either pre-calculated or in real-time involving high computation costs and time.

In this paper, a virtual regional aircraft cabin environment is embedded with multi-sensory experience for a user in order to enhance the realism and allow the user to evaluate the cabin comfort not only through visual perception, but also through acoustic perception. Our contribution proposes an adaption of existing technologies to integrate practical rendering of sound wave effects inside an aircraft cabin virtually through an untethered mixed reality device, Microsoft HoloLens2. Different approaches in auralizing an immersive aircraft cabin environment have been considered and an observation has been made between adapting wave acoustics for sound modulation inside an aircraft cabin to just placing a source for sound spatialization. The system is enabled for visualization and auralization of a virtual aircraft cabin through Microsoft HoloLens2.

2. Tools and Methods

The current project is developed for a MR HMD, Microsoft HoloLens2, for its standalone, impressive hologram resolution and spatial sound. HoloLens plays 3D sound through the small speakers above the ears determining it by using HRTF arriving at different times at ears. It uses Inter Pupillary Distance (IPD) of the HMD to adjust the HRTF’s. When a complex room or model is considered, spatial sound should no longer be limited by only direction and distance. Including other dimensions such as occlusion, reverberance, decay time, portaling, obstruction increases the immersiveness in an audio-visual sense. Collectively these dimensions are called as acoustics as depicted in *Figure 1*.

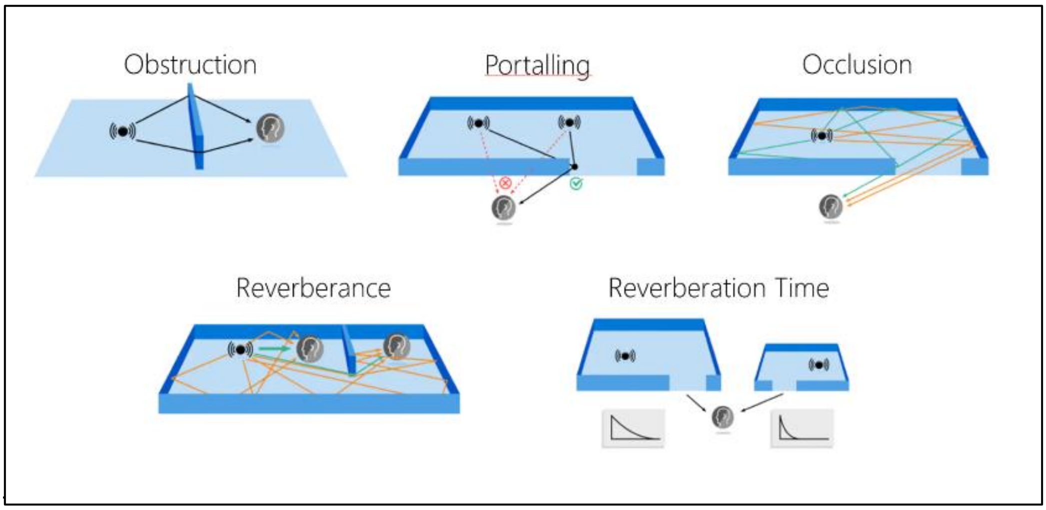

Figure 1- Sound propagation effects

The application is built in a 3D software, UNITY version 2019.4 LTS for Microsoft HoloLens2. The model of the regional aircraft is acquired from the designers and analyzed and skimmed in a CAD modelling software, Rhinoceros. After which is exported to UNITY through the desired file format. Mixed Reality Tool Kit (MRTK), a cross platform function is adapted to this project for easy app building features it provides for Microsoft HoloLens2. The audio source selected for this project is a familiar flight crew announcement of the flight destination to provide the user with more realism. In order to auralize the aircraft virtual model, UNITY provides plugins such as Microsoft Spatializer, MS HRTF Spatializer and Project Acoustics which make the Mixed Reality spatial audio development to provide natural user experience.

3.1 Software Tools.

Two different tools have been considered for auralizing the sound source inside the immersive cabin. Both, Project Acoustics Plugin and MS HRTF Spatializer Plugin, are integrated to the UNITY scenes in order to audialize the sound source.

Project Acoustics Plugin is a unique wave-based simulation in modelling acoustic effects through complex scenes quickly. It performs offline pre-computation of the scene geometry reducing the computation costs too. Project Acoustics operates on voxels, instead of mesh triangles to bring accurate wave-based propagation effects to the VR apps. With the voxels, a grid of probes is placed throughout the scene based on the navigation mesh. These are called listener positions or probe positions. For each probe point, there exists several locations to take the impulse response, each of which is a sampling position. Each probe point is then simulated and the results are pressed to a single meta data file (ACE) to be used during run time in order to drive the audio renderer. At runtime, project acoustics uses interpolation once per audio frame to produce smoother values as both the listener and sound sources move throughout the space. The plugin completely relies on the objects/meshes that reflect and occlude sound in the simulation along with the player navigation mesh that constrains listener probe points in the simulation. Accordingly, the typical workflow of the plugin happens in 3 steps: Pre-bake, Bake and Runtime.

On the other hand, unity provides MS HRTF Spatializer plugin as a part of the Windows Mixed Reality package and it runs on CPU with HoloLens applications. This can be enabled when MRTK is added to the project. The temporal and spectral cues are the reason for the spatial sound perceived with direction and distance. These are expressed in HRTFs which measure the way the sound is arriving and reaching human ears. This kind of plugin is not dependent on the environment of the model and thus does not account any acoustic parameters.

3.2 Procedure

Firstly, Project acoustics plugin is imported and integrated with the Unity project. With spatializer plugin selected to Project Acoustics, an audio mixer is created to apply the effect to the audio source. The pavement of the cabin is marked for navigation with no step height or slope as the user walks through this path inside the cabin. For this project only the lining panel, bulk head and aircraft seats are considered for acoustics geometry. Only these meshes are marked for baking acoustics with different absorption coefficients of the material. The values of absorption coefficients are approximated through the common material selection of an aircraft cabin to determine the amount of sound energy that can be reflected from each surface. Reverbation time of a given material inside the cabin is inversely proportional to its absorption coefficient. Thus, materials with smaller absorption values (0-0.2) are more reflective than with higher absorption values (0.7-1.0) [16]. All the other materials of the cabin are set to UNITY's default selection. Once the navigation and materials are set, the cabin is calculated for the probe points i.e the listener points *Figure 4*. Number of probe points define the listener point locations where the simulation results are interpolated.
Considering the scene geometry of the cabin, fine resolution has been considered for voxel size. The green boxes in the figure corresponds to the voxel volume of the scene meshes and are determined by the simulation frequency. When a voxel has a geometry of the cabin, it is tagged with the absorption coefficient as given to that mesh. The overall pre-bake time for this scene has been estimated as approximately 2hours and the cost of baking at 10 hours. The baking process has been performed locally on the PC with Docker Desktop to process the simulation. The resulting ACE file is re-imported and added to UNITY scene.

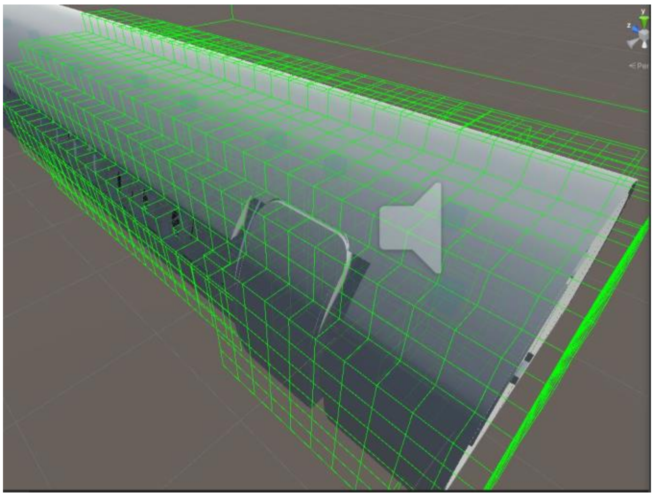

Figure 2 - Calculated Voxels of the aircraft cabin

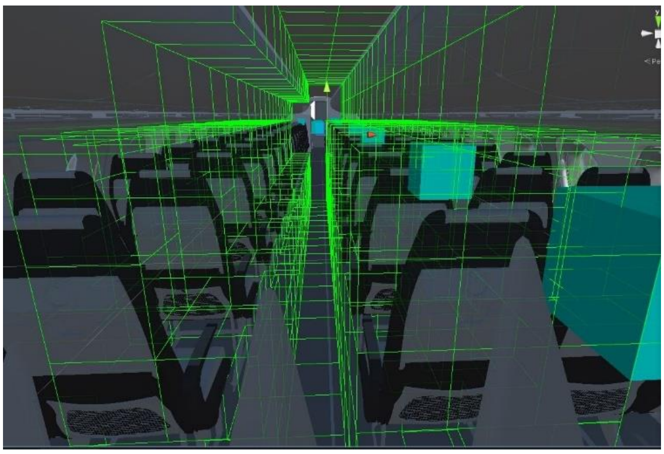

Figure 3 - Voxels and probe points inside the cabin

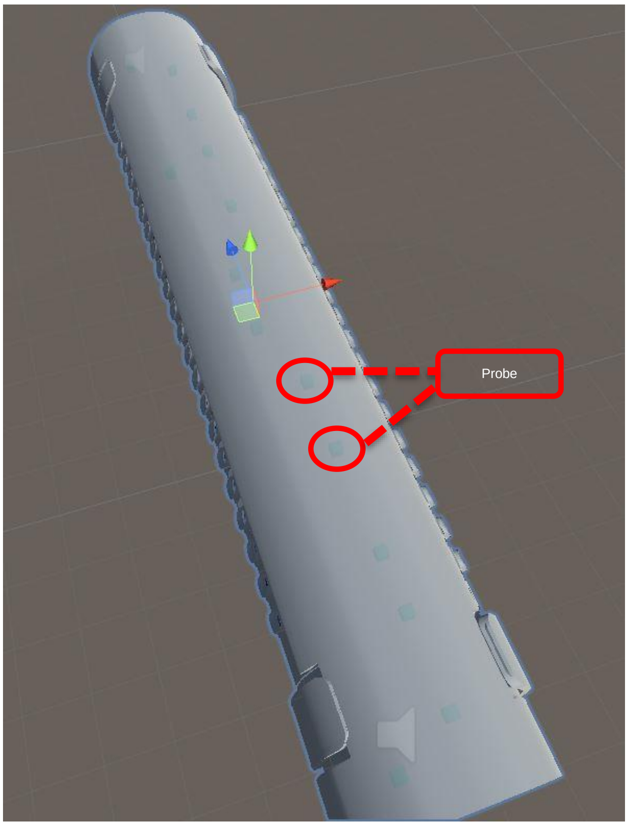

Figure 4 - Probe point positions

Finally, the same cabin geometry is then exploited for a different spatializer through a different scene in UNITY, MS HRTF Spatializer, to understand the difference between auralization inside the cabin. With MS HRTF spatializer selected from the settings, the scene is configured for distance-based attenuation and Reverb properties. Spatial Blend is set to 3D in this scene too to auralize the sound source for 3D aircraft cabin environment.

3.3 Visualization of field maps and modal shapes

Another application of the VR or AR for acoustic is the possibility for engineers and designers to visualize the acoustic footprint, in terms of pressure, vibrations or modal shape, directly on the components in a virtual environment. In this way, we want to provide to the several "insiders" in the aircraft and cabin design, a tool to understand the most critical positions, components, etc. for different frequencies, flight phases and configuration. In particular, we exploit vibro-acoustic results obtained in work on a regional aircraft [3][17]. These works developed a finite element model of an aircraft fuselage, to study the performances of new acoustic solution in the frequency domain for low frequency. The FEM model has the following elements: fuselage panels and stiffeners, cabin panels and floor, overheads and seats. The results are not completely suitable for an auralization because they don't cover the whole frequency range of the human ear (from 20 *Hz* to 20000 *Hz*) and moreover they only consider the pressure generated by the engine on the fuselage panels.
Four types of results are used, the pressure map on the passenger cabin (placed on the cabin panels), and the modal shape of the lining panels, assuming all the components of the cabin coupled together. From Figure 5, it is possible to see the complexity and the number of data and information that designers have to process and analyze. Therefore, this type of visualization could help to have a global view of the acoustic problem in the cabin.

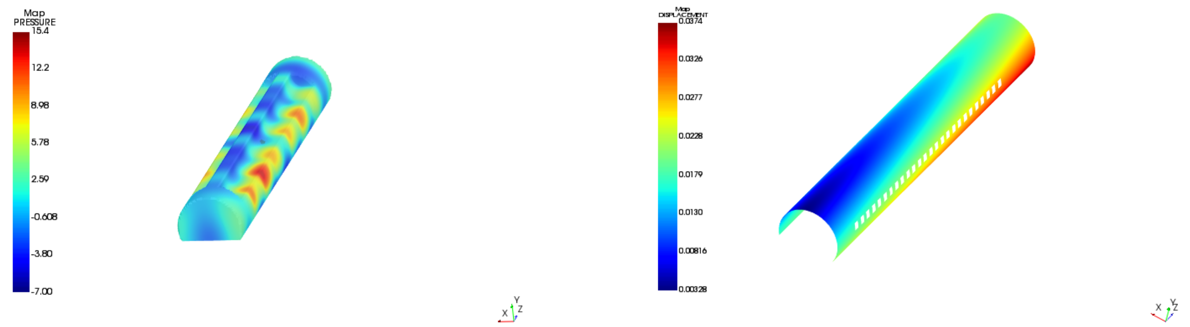

Figure 5 - Pressure on the passenger cavity and displacement map (modal shape) of cabin lining panels used for visualization.

3. Sound Perception through different tools

Before deploying both scenes to Microsoft HoloLens, they are played on desktop UNITY application with spatial sound of the desktop turned on. The camera position depicts the user movement along the navigation i.e., the pavement of the aircraft cabin in order to auralize the sound in different aspects. The simulation has been repeated implementing two different tools (Project Acoustics and MS HRTF Spatializer plugin) and also by changing the audio source position from inside (near the Flight attendant seat) and outside the cabin in order to identify the one which allows to properly generate the sound to be perceived by the user in the VR environment. It is to be noted that being aircraft cabin a closed environment, the audio should be heard same throughout the cabin.

With Project acoustics plugin, when the audio source is placed inside the cabin, with the change in camera position no change in audialization has been encountered. In fact, the entire cabin has been observed to have occlusion and reverberance effects suited. When the audio source placed outside the cabin and camera position moving inside the cabin, no sound could be heard throughout the cabin. This could be due to the absorption coefficient given to the lining panel and the bulkhead of the aircraft cabin.

On the other hand, with MS HRTF Spatlializer plugin, the audio magnitude decreased with distance and can only be heard through the direction of placement of the source.

	AudioSource Position	Plugin	Observation
T1	Inside the cabin	Microsoft Acoustics	Occlusion and Reverberance effects
		MS HRTF	Audio magnitude decreased with distance
T2	Outside the cabin	Microsoft Acoustics	When entered the cabin, no sound can be heard
		MS HRTF	Audio magnitude decreased with distance and sound can be heard with direction cue

Table 1 - Observation of both tools

It has been observed that the use of the Project Acoustic plugin will be useful in order to have basic information of the noise in the cabin. The core of the problem will be the right definition of material coefficients of absorption, taking in account the complex kinematic behavior of the aircraft materials. The source definition for a particular kind of aircraft is challenging problem in numerical analysis too. For this reason, it is necessary to combine numerical simulation results (from FEM, SEA software) as audio input in the virtual mockup end the Project Acoustic features. It will be possible to reduce the amount of data imported (and generated) by simulation and increase the realism of the mockup. Finally, field maps (pressure or vibrations) imported in the virtual mockup could help in the validation of this approach, directly giving a feedback between the numerical output and the auralization.

4. Conclusion

Sound plays a major role in improving user experience by providing realism and immersion inside the virtual environment. When it comes to aircraft cabins, engineers and designers around the world are working on aircraft noise to reduce the effect of it and increase the passenger well-being. With advent growth of innovative tools, virtual reality solutions are adapted to pre-manufacturing phases of the design for design validation by involving potential users inside the environment. Although this practice has always been proven for evaluating the visual aspects of a design through immersive environment, other aspects like sound, touch capabilities have been limited. In this paper we introduced a multi-sensory immersive environment for improving user perception within virtual reality. Auralization of a sound inside a room scene should consider not only the sound source simulation but also the room acoustics in designing a perfect cabin structure. In this regards, Project Acoustics Plugin has been considered for simulating wave acoustics inside the aircraft cabin by taking in to account the acoustic parameters such as occlusion, reverberance, obstruction etc. A set of absorption coefficients have been weighed in viz, for bulk head, lining panel and the seats of the aircraft cabin in order to compute the simulation. At the same time, the same cabin has been simulated with a different plugin, MS HRTF Spatializer to adapt the cabin to distance-based attenuation and reverberance.

It has been observed that the Project acoustics plugin added a more realistic feel to the audio source by considering the factors of the structure of the cabin whereas the MS HRTF plugin has been able to only auralize the sound based on distance and direction. The application developed can thus be modified with different acoustic material properties and audialize the sound inside the aircraft cabin before the prototype phase reducing significant time and costs.

In the future, the scenes are planned to be deployed to Microsoft HoloLens2 and real users will be placed inside the environment to experience both plugins and provide user feedback. Moreover, the noise from acoustic analyses or on field measurements (if it is possible) are planned to be applied in the virtual model, exploiting both the Project Acoustic features and numerical tools as FEM and SEA based software. Therefore, a real user will validate acoustic solutions as those presented in [17].

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6. Copyright Statement

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