


# NUMERICAL PREDICTION OF CABIN NOISE FOR FUTURE SHORT-HAUL AIRCRAFT IN EARLY AIRCRAFT DESIGN

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## Abstract

The climate targets set out in the “European Green Deal” call for the consideration and implementation of climate-friendly propulsion concepts and sustainable fuels in future aircraft configurations. This puts the use of very efficient propeller engines into the focus of aircraft design. As they yield high, tonal sound pressure levels on the fuselage, especially in the low-frequency regime, these pose major challenges to cabin acoustics. The design of noise control measures for these aircraft configurations requires the competence to predict the resulting interior noise as early as possible in the design process of the vehicle in order to evaluate their effectiveness. Cabin noise prediction necessitates a high level of geometric and structural detail regarding the fuselage structure and cabin components while maintaining consistency to the overall aircraft as well as structural design.

To this end, a knowledge-based engineering (KBE) methodology is examined and adopted in the Python programming language as FUSELAGE GEOMETRY ASSEMBLER (FUGA). FUGA extends the preliminary design data with design knowledge sufficient for detailed numerical analyses. This paper describes the knowledge-based geometry and vibro-acoustic model generation process in FUGA, which can consider the necessary level of detail for the cabin noise prediction already in the preliminary design and its implementation in the structural design landscape at the DLR. For this purpose, vehicle data sets in the data format COMMON PARAMETRIC AIRCRAFT CONFIGURATION SCHEMA (CPACS) form the modelling basis. Originating from the aircraft preliminary design, these initially describe the outer shell of the vehicle and are extended by detailed structural information that defines the geometric boundary conditions for component placement in cabin design. For the cabin components, the open-source geometry kernel OPEN CASCADE TECHNOLOGY (OCCT) is used to provide geometries at the level of detail required for subsequent analyses. The geometry models are then discretized using the open source meshing library GMSH and further used for numerical analysis. With the use of the standardized CPACS data format used across distributed structural sizing competences, realistically dimensioned structure models can be considered in the acoustic transmission behaviour.

Furthermore, the propeller design capabilities are coupled to the propeller near field noise prediction to generate the excitation field for vibro-acoustic models. Finally, the prediction of cabin noise is carried out for short-haul propeller-driven aircraft concepts designed within the DLR project EXACT (Exploration of Electric Aircraft Concepts and Technologies, `https://exact-dlr.de`) and the interior noise for the aircraft using different energy carriers like kerosene and liquid hydrogen is compared.

**Keywords:** Aircraft cabin, Cabin noise, Noise prediction

## 1 Introduction

The numerical prediction of aircraft cabin noise requires detailed geometry and design knowledge of the interior fuselage structures, cabin components and overall mass distributions. This knowledge is usually not available in the early design stages of an aircraft and certainly not in the conceptual design phase.Due to the complex nature of sound generation and propagation into the aircraft cabin it is not possible to create an empirical database for use in conceptual aircraft design. Therefore, one has to rely on physical methods to evaluate the interior noise in the early design stages.

The early aircraft design stages usually deal with large designs of experiments to narrow down the number of viable candidates. This results in the need for rapid evaluation competences. While the statistical energy analysis (SEA) allows a fast calculation of aircraft interior noise for broadband excitations [1, 2], it is only valid in the high-frequency domain. Wave-resolving noise prediction methods [3, 4, 5] based on the finite element method on the other hand require specialized model setup and properties, which are not typically available in early aircraft design stages. Therefore, no direct link between aircraft design and cabin noise prediction can be found in the literature. This contribution therefore describes a digital thread, seamlessly connecting aircraft and propulsion design, structural and cabin design processes to the numerical cabin noise prediction. This is made possible by utilizing CPACS as a common data model for exchange of vehicle data. This process builds on the CPACS fuselage structural definition as published by SCHERER and KOHLGRÜBER [6] as well as the cabin definition by WALTHER ET AL. [7]. Relevant structures are first designed in a CPACS file and then wave-resolving FE models are generated from it using FUGA.SIMULATION [8, 9], a submodule developed for the simulation model generation in the FUGA framework [10, 11].
The methodologies used in this study along with its interfaces as implemented in the digital thread are described in Section 2. The proposed methods are applied to the numerical cabin noise prediction to two aircraft concepts in Section 3. Section 4 concludes this study and highlights potentials for further examination.

## 2 Digital Thread for Cabin Noise Prediction

This section describes the developed methods for the numerical prediction of the interior noise from aircraft preliminary design data. The methodologies and design tool interfaces are presented in Section 2.1. Then, the vibro-acoustic model generation process using the FUGA framework is described in more detail in Section 2.2.

### 2.1 Methodologies and Interfaces

For the numerical cabin noise prediction of aircraft, the design of the propulsion system, fuselage and wing structure as well as cabin needs to be carried in addition to the overall aircraft design. Different design methodologies are developed and used here, where the aircraft data exchange via CPACS ensures the consistent use of model data. A graphical representation of the digital thread in the form of an eXtended Design Structure Matrix (XDSM) is depicted in Figure 1 where the process is initiated with the overall aircraft design using OPENAD [12]. Here, the initial aircraft design is instantiated as a CPACS dataset utilizing mostly handbook and empirical methods for a overall, multi-disciplinary analysis and optimization. The initial aircraft design is used in OPENPROP [13] for the design and sizing of the propeller using the blade element momentum theory. This design is based on the thrust requirements from OPENAD. The detailed propeller data is used in combination with an analytical noise source model and a fast multipole boundary element method to evaluate the near field noise of the propeller. The source model is based on [14] and includes the contribution from thickness, thrust and power- or torque noise. For the propagation of the propeller noise to the fuselage, the DLR solver FMCAS [15] (Fast Multipole Code for Acoustic Shielding) is employed. The submodule FUGA.DESIGN utilizes a graph-based KBE methodology and creates the initial structure and cabin layout for the aircraft design [10, 16]. The initial structural model is extended with the ground and flight load cases using LOADZERO and LGLOADZERO [17], while the fuselage and wing structures are sized using PANDORA [18] and LIGHTWORKS [19] respectively. Here, the skin panel thicknesses of the load-bearing fuselage and wingbox components are dimensioned in such a way to withhold the occurring loads during flight and ground operation using a fully stressed design approach. This dimensioning process majorly influences the acoustic transmission behaviour into the cabin and the results are written back to CPACS in order to be considered for the vibro-acoustic model generation process.
The high-fidelity model generation process based on the sized structure models in CPACS is carried out using FUGA.SIMULATION [8]. Here, detailed wave-resolving models of the fuselage, wing and cabin structures as well as acoustic cavities are assembled and the fluid-structure-interaction is setup in a solver-agnostic way. In this study, the resulting solver-agnostic finite element models are

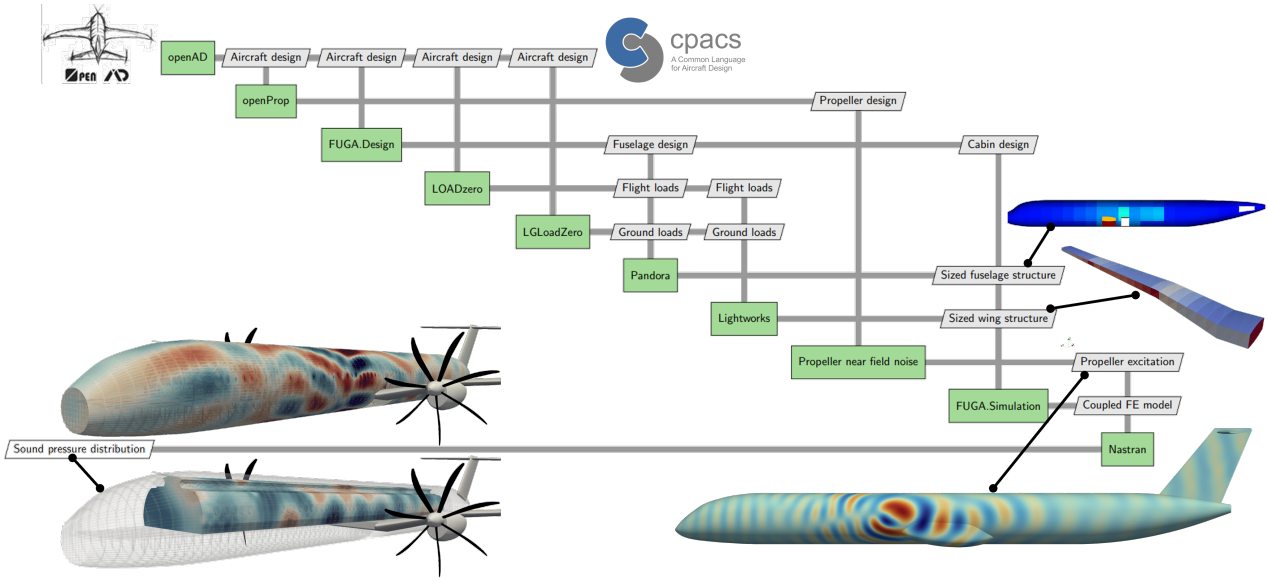



Figure 1 – XDSM of the developed digital thread for evaluation of aircraft cabin noise

converted to the Nastran format using an automated process. The near-field propeller noise distribution is interpolated to the fuselage structure where it acts as an excitation for the vibro-acoustic model. The model is solved in Nastran and the sound pressure distribution in the passenger cabin is evaluated. The model generation process is described in the following section.

## 2.2 Vibro-acoustic model generation

This section introduces the vibro-acoustic model generation process via the FUGA framework for fuselage integration and cabin design. FUGA implements a graph-based KBE methodology in the Python programming language allowing direct creation, placement, modification and meshing of airframe and cabin geometries via a built-in CAD kernel and meshing library. That way, it provides multi-model generation capabilities to enable consistent analysis model setup at various levels of fidelity. Built upon CPACS as central data model, the approach combines sets of parameters and executable rules, formulated in a declarative manner to assemble a knowledge graph. As shown by WALTHER in [11], the graph-based formulation provides a number of benefits, e.g. the possibility to trace dependencies between parameters and incorporate new design knowledge in a modular manner. Assembling knowledge and rules in a directed acyclic graph enables the use of concepts like lazy evaluation, caching and invalidation in the design process. The latter fact enables the flexible extension to different use-cases like cargo design [20] as well as hydrogen tank design and system integration [16]. Furthermore, the program flow is determined dynamically at run time, based on user requests. Consequently, rules are not executed until they are needed to fulfil a user request, thus avoiding the unnecessary performance of computationally expensive tasks. This is especially useful for vibro-acoustic model generation using FUGA.SIMULATION, which requires the highest fidelity geometries and highly resolved mesh setup.

In FUGA.SIMULATION, each component is created as a geometry and then meshed according to requirements from the use-case at hand. Utilizing Python bindings to the low-level C++-libraries OCCT (`https://dev.opencascade.org/`, [21]) and GMSH [22] as well as leveraging performant multithreaded boolean operations and mesh generation, typical pythonic bottlenecks are avoided. Therefore, the model setup of highly detailed meshes remains efficient. Exemplary vibro-acoustic models and the achieved level of fidelity with a targeted element size of $0.05$ m are shown in Figure 2. Due to the graph-based nature of the knowledge repository implemented in FUGA, additional design and model generation rules can be integrated efficiently, while the full geometry-based meshing process allows to flexibly extend the modelling capabilities. Additional design details were integrated in the model generation process for vibro-acoustic FE models used in this study. While extensions in [9] integrated rules for automated generation of design details like seat models in the structural and

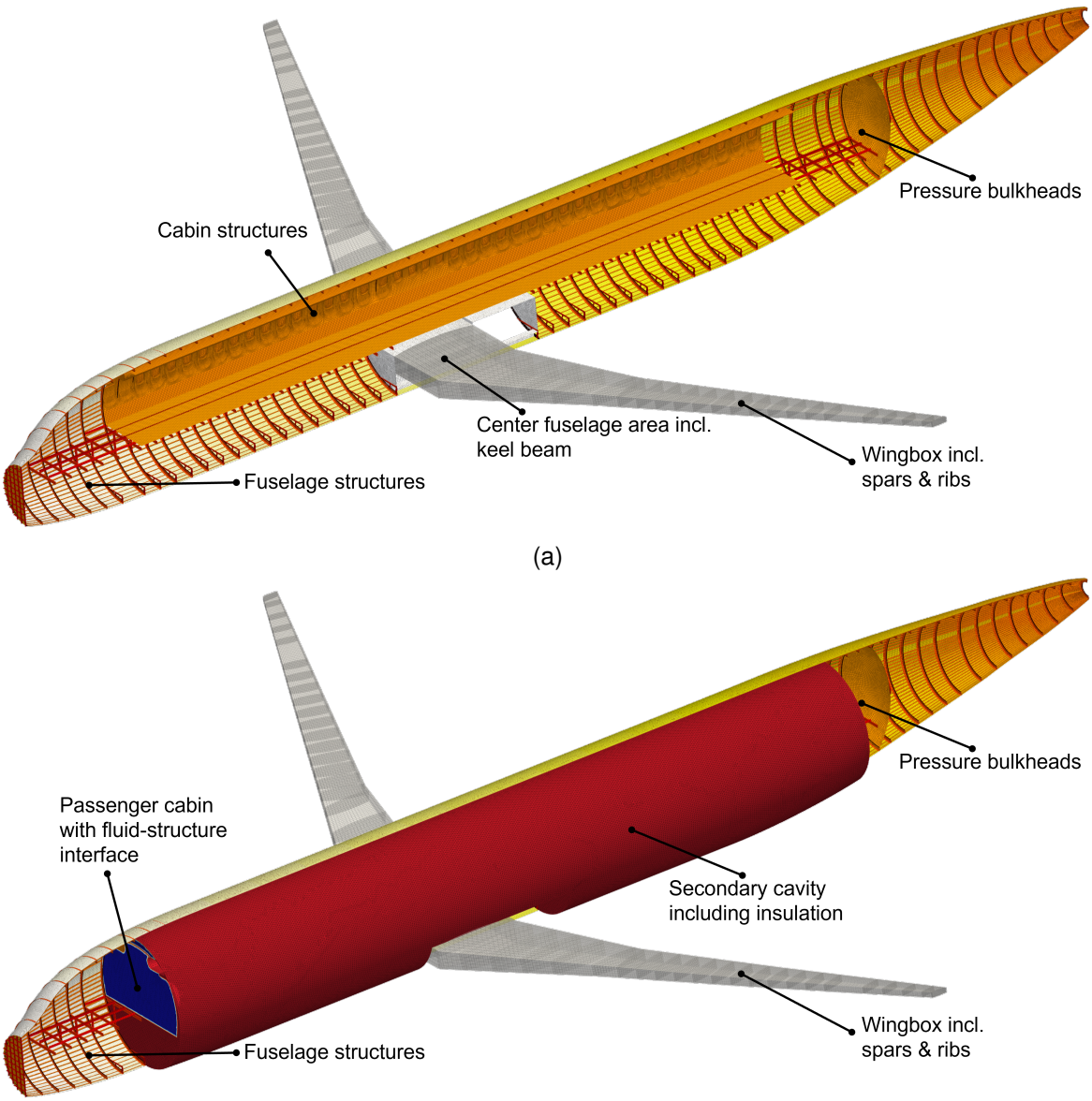



Figure 2 – Vibro-acoustic aircraft models of primary and cabin structures (a) as well as acoustic cavities (b)

acoustic domain as well as the thermal-acoustic insulation, which are also used in the current study, further structural extensions are described here. E.g. the structural design of the center fuselage area as well as the wave-resolving mesh generation for these structures is extended to ensure a physically meaningful load introduction from the wing to the fuselage. The CPACS definition of the center fuselage area is based on [6] and the wave-resolving mesh including shell (orange) and beam (blue) elements is depicted in Figure 3(a). To make comparisons between aircraft concepts using different energy carriers, the respective fuel tanks are also integrated in the model generation process. The energy carrier inside the rear mounted hydrogen tanks as well as kerosene inside the wing tank are illustrated in Figures 3(b) and (c), respectively. Existing routines for the fluid modelling as well as the fluid-structure-interaction are reused from the cabin modelling here. As for the structural liquid hydrogen tank concept, different attachment concepts from [16] are available, e.g. a supporting, polar and strut mount. Here, the supporting mount concept is employed in the present study as depicted in orange in Figure 3(c). This utilizes crossbeams attached to the frames and four support struts per crossbeam.

These automatically created vibro-acoustic models can subsequently be used to calculate the vibration field of the structural models and the cabin noise distribution inside the passenger cabin while

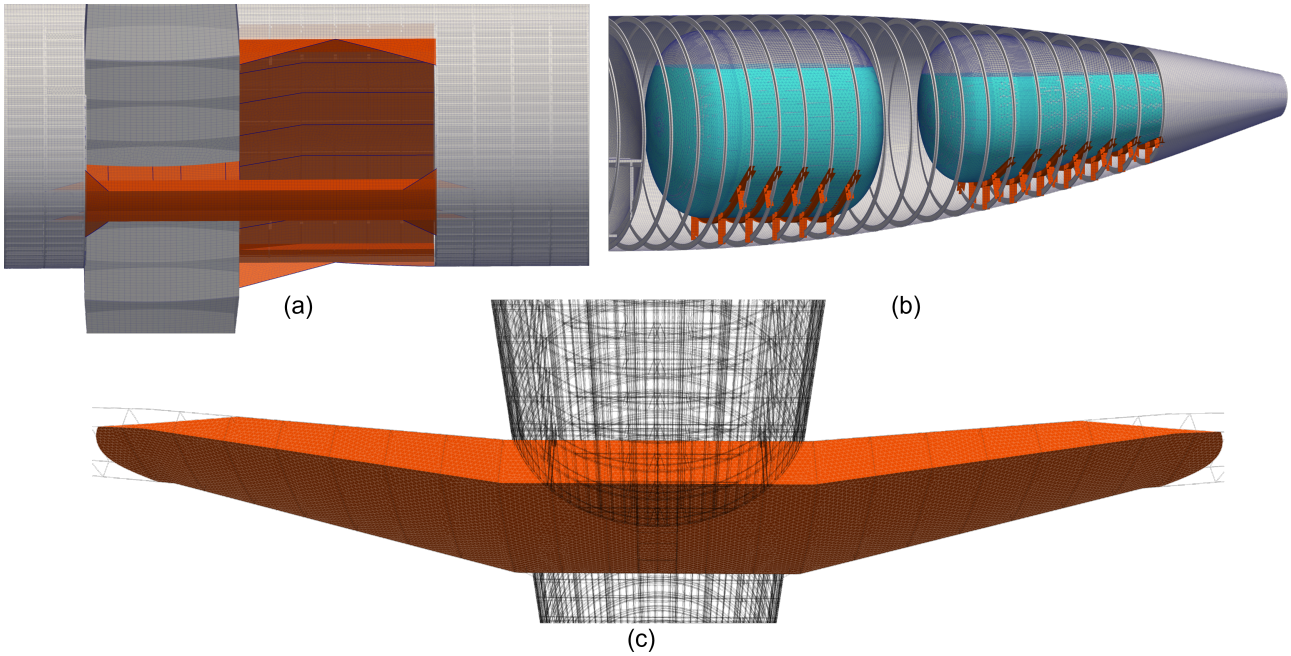



Figure 3 – Vibro-acoustic model extensions for center fuselage area (a) as well as liquid hydrogen (b) as well as wing tanks (c)

taking into account specific model details from the respective energy carriers used in the aircraft.

## 3 Cabin Noise Prediction

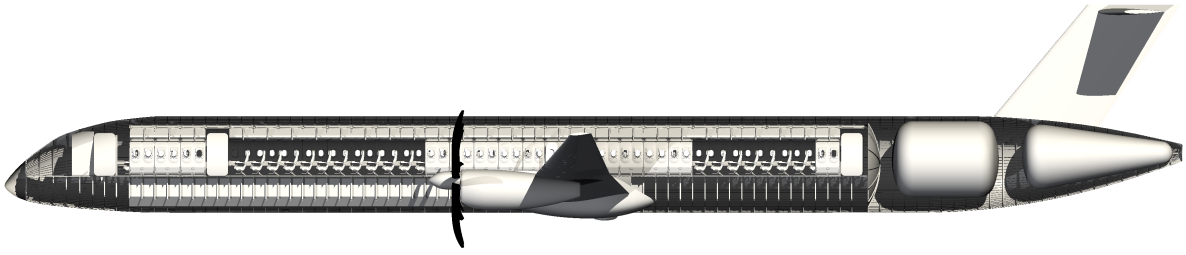
This section briefly describes the two aircraft configurations employing different energy carriers and presents the numerical study using the methodologies described in the preceding section.

### 3.1 Aircraft configurations

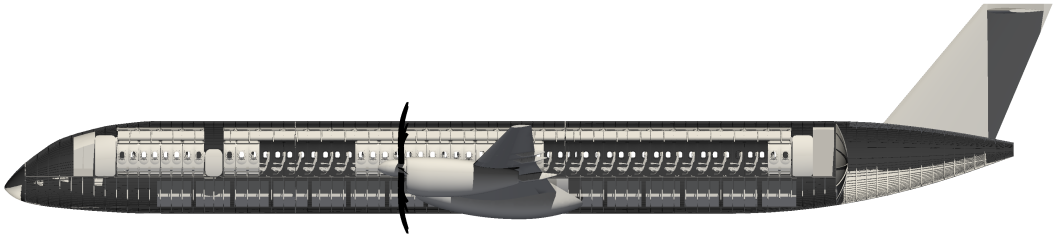
Two aircraft concepts from the EXACT project assuming different energy carriers are addressed in this study. The two concepts are shown in Figure 4. Both aircraft are designed to accommodate $240$ passengers and have a design range of $1500$ nautical miles. The aircraft concept $\mathbb{A}_1$ uses liquid hydrogen as energy carrier. It features a mild-hybrid engine architecture, where a gas turbine provides the power to drive the propeller during the majority of the flight phases including cruise condition. An additional electric motor driven by a fuel-cell is used to optimize off-design aircraft operation such as taxi and descent. For a detailed description of the hybrid engine architecture, the reader is referred to ATANASOV and SILBERHORN [23]. The liquid hydrogen is stored inside two tanks in the rear fuselage behind the pressure bulkhead.
In contrast, the aircraft concept $\mathbb{A}_2$ utilizes a gas turbine driven by kerosene stored in three segments along the wing span in wingbox-integrated tanks. For both aircraft concepts the design process is carried out as described in the preceding section and the vibro-acoustic models are generated. The following section describes the cabin noise prediction and the vibro-acoustic evaluation.

### 3.2 Vibro-acoustic evaluation

The interior noise evaluations for the two aircraft concepts are presented in this section from a harmonic analysis in Nastran. The resulting coupled vibro-acoustic FE models consist of $> 15 \cdot 10^6$ degrees of freedoms and unsymmetric system matrices. The solution in Nastran on a CPU of the type Intel Xeon Gold 6444Y@$3.60$ GHz using $8$ cores takes $\approx 70$ minutes per frequency step and utilizes memory of more than $400$ GB.
The cabin noise prediction in mid cruise condition is carried out for the first three harmonics of the propeller blade passing frequency (BPF). The resulting cabin noise distribution for the aircraft concept $\mathbb{A}_1$ is shown in Figure 5. It is depicted in a plane on ear level of the passengers. In particular, in the fundamental BPF a high sound pressure level (SPL) occurs across the entire length of the cabin. In



(a) Aircraft configuration $\mathbb{A}_1$



(b) Aircraft configuration $\mathbb{A}_2$

Figure 4 – Aircraft concepts considered for cabin noise prediction

the second harmonic of the BPF, the internal sound field is much more localised in the area around the propeller plane. The third harmonic yields again much lower noise and this tone will presumably be masked by other noise sources like the turbulent boundary layer.
It should be noted, that cabin noise for this aircraft was predicted in [9] using a configuration from a prior design loop. In this current version, the propeller design has been changed from using $9$ to $10$ propeller blades, which results in a lower rotation frequency and therefore a reduced noise footprint of the propeller on the fuselage. In consequence, the resulting cabin noise distribution is also reduced significantly here.

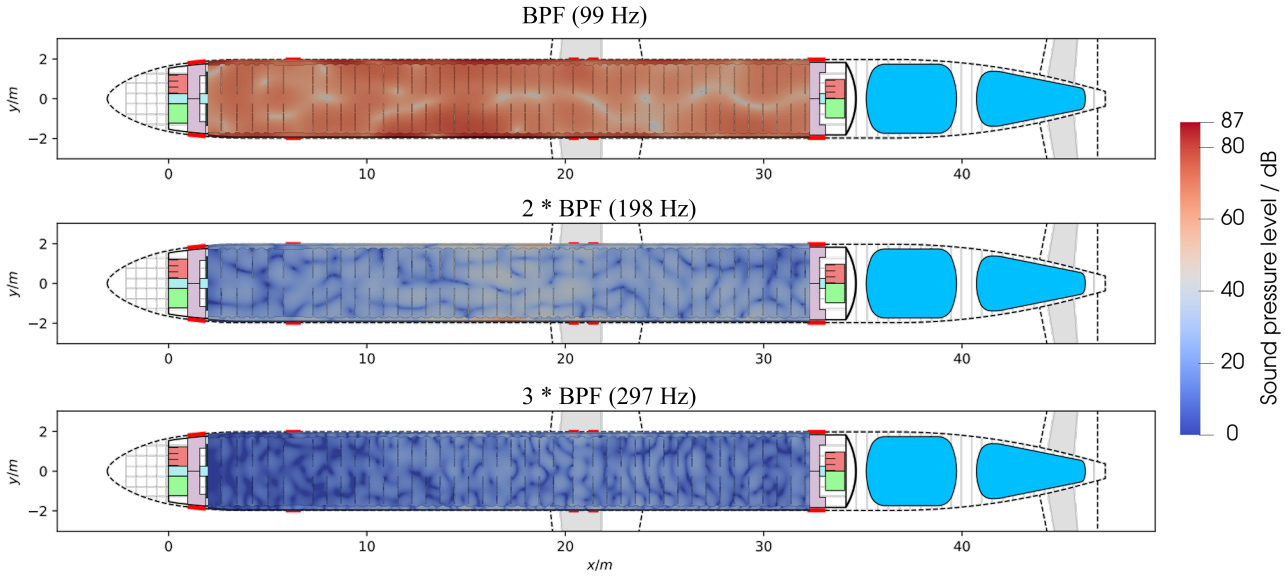



Figure 5 – Noise distribution in the passenger cabin of the aircraft $\mathbb{A}_1$

In comparison, Figure 6 shows the resulting cabin noise distribution for aircraft concept $\mathbb{A}_2$ using the kerosene energy carrier. The two propeller designs yield slightly varying rotation frequencies for the two aircraft due to different thrust requirements, hence the different BPFs. In general, it can be observed, that the cabin noise in the fundamental BPF here is slightly lower than for aircraft $\mathbb{A}_1$. This is due to the higher thrust setting and resulting shaft power of the propeller in cruise condition, which is necessary due to the longer fuselage to account for the liquid hydrogen tanks.

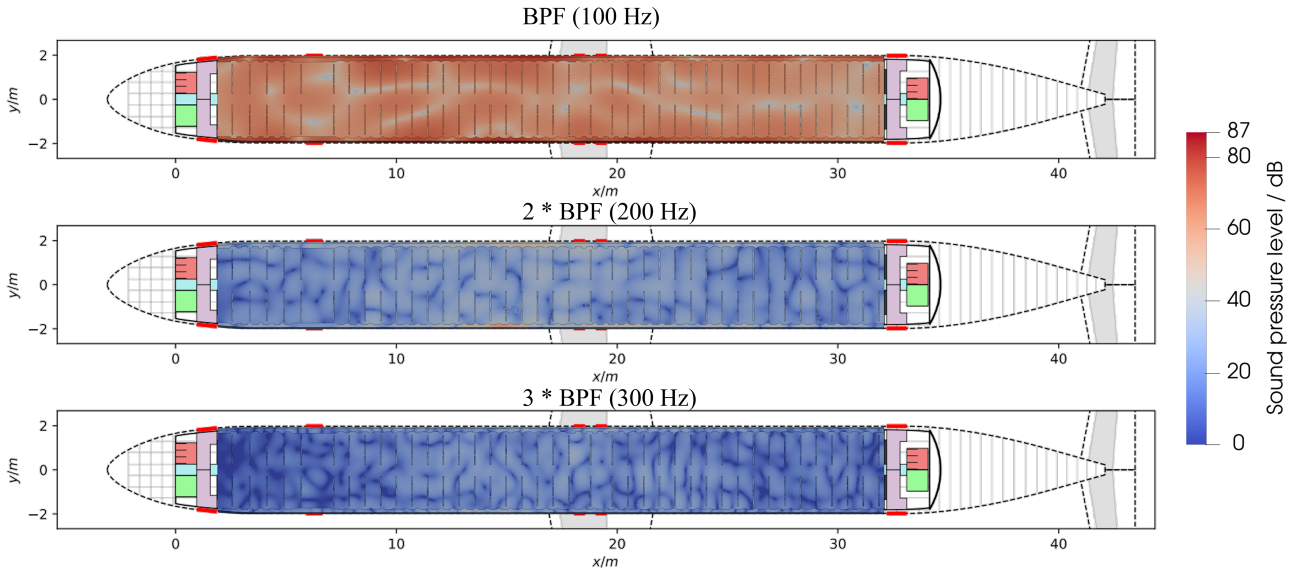



Figure 6 – Noise distribution in the passenger cabin of the aircraft $\mathbb{A}_2$

Overall, by calculating the energetic average along the passenger cabin, the hydrogen aicraft $\mathbb{A}_1$ yields a mean SPL which is $3.2\,\text{dB}$ higher than the kerosene aircraft $\mathbb{A}_2$ in the fundamental BPF due to increased thrust requirements. The second and third harmonic amount to averaged cabin noise levels for the hydrogen aircraft of $1.7\,\text{dB}$ higher and $2.2\,\text{dB}$ lower compared to aircraft $\mathbb{A}_2$, respectively. However, the second and third harmonic in both aircraft have mean SPLs of $\approx 35\,\text{dB}$ and $\approx 45..50\,\text{dB}$ below the fundamental BPF. Therefore, the latter should be addressed for additional noise control measures. To this end, the authors [9] showed a lot of further noise reduction potential via the integration of tuned mass dampers at the frame-stringer-intersections around the propeller plane, which are tuned to the BPF. Even higher noise reduction combined with less additional system mass was shown via the use of active noise control on a prior version of aircraft $\mathbb{A}_1$ by KOCHAN [24].

## 4 Conclusion

This article presents a digital thread for the numerical prediction of cabin noise in the context of preliminary aircraft design, in which methods for the design of the overall aircraft concept, fuselage and wing structure, cabin and propeller are digitally integrated. Vehicle data is exchanged in the CPACS format to ensure that consistent data is used throughout the process. The design processes are linked with methods for propeller noise prediction and wave-resolving, vibro-acoustic simulation. CPACS also forms the basis for detailed model generation using FUGA.SIMULATION, which builds on the results of structural fuselage and wing dimensioning. This enables structural models that can withstand the loads encountered during operation to be considered in cabin noise prediction. That way, consistent models can be used in the context of overall aircraft design for structural investigations, cabin noise predictions and also other disciplines.

The digital thread for cabin noise prediction is exemplified using two aircraft concepts assuming different energy carriers. Numerous enhancements to the structural and acoustic modelling process for interior noise prediction models are highlighted, which allow to compare the influence of the respective energy carrier on the vibro-acoustic transmission into the passenger cabin. A slightly higher interior noise level is observed for the aircract concept $\mathbb{A}_1$ which utilizes liquid hydrogen as energy carrier due to higher thrust requirements. This study can serve as a basis for future investigations optimizing the aircraft regarding cabin noise either via modifying the propeller design or the integration and optimization of noise control measures regarding their placement. In this study, cabin noise prediction sequentially follows structural design. To be integrated into the design process as an equal discipline, it can potentially be regarded as part of multidisciplinary analysis and optimisation (MDAO), which can be achieved, e.g. with the aid of data-driven surrogate models [25]. In particular, the automated integration of propeller design and noise prediction can open up the design space suf-

ficiently to reconcile aircraft designs optimised for cabin noise with the requirements for lightweight construction and flight characteristics.

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