MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Vibroacoustic Evaluation and Optimization of Aircraft Cabin Concepts - A Systems Engineering Framework

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ABSTRACT

Concepts such as model based systems engineering (MBSE) and multi-disciplinary design optimization (MDO) are increasingly used for the design of complex products. In order to describe new innovative cabin designs and its interrelations with other aircraft components an MBSE approach is motivated. Furthermore, MDO methods enable a holistic design optimization on the foundation of this model-based description. In order to facilitate an efficient exchange of data and parameters between numerical tools of different disciplines, a central data model is needed. Such a central data model is used in the present study for the assessment of vibro and cabin acoustics. This paper proposes a wholistic framework for the evaluation of aircraft cabin noise. This framework is intended as a foundation for futher optimizations regarding aircraft interior noise. The use of a model-centric data exchange enables a consistent integration of different system models into a fully automated workflow. The system models represent empirical, analytical and numerical evaluations of different acoustic disciplines. The overall aim of the methodology is an enhancement of the processes and the development of new tools which facilitate the network of different partners engaged in the vibroacoustic evaluation of cabin concepts.

Keywords: Cabin acoustics, model-based design, cabin design
I-INCE Classification of Subject Number: 76

1. SYSTEMS ENGINEERING IN CABIN ACOUSTICS

Current aircraft design experiences an increasing demand for the exchange of a large bulk of data over different development steps and various disciplines with contrasting

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requirements. Introducing changes in one discipline can significantly affect other disciplines; these relations are often elusive and not identifiable. In addition, a lot of diverse software and tools are used by the involved partners for the individual analyses. This may lead to incompatibilities, loss of information or memory-intensive transfer of redundant data.

These challenges are especially apparent in the field of cabin acoustics which has been shown by Thomas and Scheel [1]. When a supplier of the secondary structure (e.g. lining and ceiling panels or overhead compartments) changes the construction type or the materials, extensive manual effort is necessary to incorporate these changes in the digital models used for the calculation of noise transmission into the aircraft cabin. Prescribing certain requirements for the (acoustic) properties in order to optimize the design can then lead to instructions which are not necessarily comprehensible for the supplier. This is due to the lack of a common language spoken by all partners involved. Also, the evaluation of cabin noise involves many disciplines which work with largely heterogenic data. The noise transmission into the interior is often evaluated using deterministic methods, like the finite element method (FEM). However, many noise sources are random in nature and need to be coupled with the deterministic approaches. This gets further complicated by the increased use of model order reduction techniques which describe the system dynamics projected in certain (modal or wavenumber) spaces of reduced dimensionality.

In addition, the design and evaluation of noise reduction treatments need to be executed in a wholistic framework, as shown by Omais [2]. Here, a noise reduction of a blade design for a counter-rotating open rotor (CROR) engine has been optimized in an isolated condition which led to a tonal noise reduction at the fundamental blade passing frequency of more than 35 dB in sound pressure level. In an installed condition, i.e. by taking into account the aero-vibro-acoustical installation effects this noise reduction has been degraded to about 2 dB.

An approach to address these challenges using model-based procedures is proposed by the authors in [3]. Disciplinary models for the evaluation of cabin (vibro-)acoustics, geometry and mass of the secondary structure as well as the volume of the secondary cavity are derived from a central data model. System models are interconnected in order to optimize the design regarding the multitude of disciplines. This study extends the approach by including system models which describe the in-flight noise sources. These are namely the self-noise of the turbulent boundary layer (TBL) as well as the random mixing noise of the engine jet. As the latter one also interacts with the shear layer of the turbulent flow, simplified models are choosen to model scattering and refraction effects analytically.

The evaluation and optimization of cabin noise necessitates the integration of numerous disciplines and competences. These competences are usually distributed between different specialists, departments or even companies and suppliers. This necessitates a fully integrated aircraft design process from the basic mission definition through the different noise sources to the noise receiver, e.i. the passenger. A sequence plan for a multi-disciplinary design optimization (MDO) approach is given in Figure 1. This portrays the model-centric evaluation process by coupling the distributed competences via a central data model. The centralized optimization procedure tracks the requirements and targets for the given analysis and iterates the performance over the parameter design space. Via decoupling of the competences a high flexibility in the overall optimization process is achieved. This is because large alterations can be investigated without manually modifying the overall process.

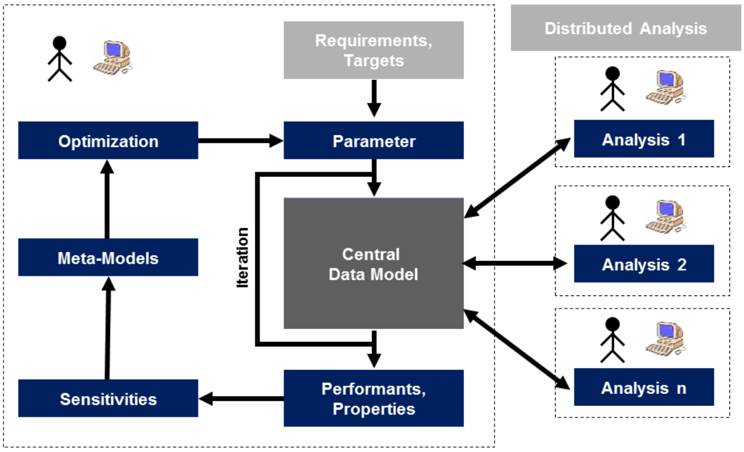

Figure 1: Examplary sequence plan for multi-disciplinary design optimization

2. EVALUATION FRAMEWORK

The Acoustic Flight-LAB Demonstrator as test-structure as well as its model-based description in a wholistic evaluation framework are introduced in this section. System models describing the different noise sources as well as the evaluation process are presented. The evaluation procedure incorporates the engine predesign for a given mission cruise condition, a subsequent evaluation of the jet mixing noise as well as the noise generated by the turbulent boundary layer. Also the interaction of the jet noise with the boundary layer are adressed in an acoustical transmission model. The different noise excitations are generated for the vibroacoustic model and the execution of the latter one concludes the evaluation procedure.

2.2.1. Acoustic Flight-LAB Demonstrator

The analysed test structure is the Acoustic Flight-LAB Demonstrator shown in Figure 2 inside its testing environment, located at the Center of Applied Aeronautical Research (ZAL) in Hamburg. The fuselage section of 8.5 m length has a diameter of approximately 4 m and is based on a short-range narrow-body passenger aircraft made from aluminum. The demonstrator has a floor for the passenger cabin as well as for the cargo bay. The floor is mounted at every frame position via a crossbeams and two struts to the fuselage. The skin is stiffened with 87 stringers in circumferencial and 17 frames in longitudinal direction. It therefore consists of 1392 skin field and has an approximate mass of 1400 kg.

The demonstrator is mounted between two portals and supported by four very soft air springs, which decouple the structure from the support. Both endings of the fuselage structure are isolated with acoustic absorbers. The foundation for this study is the vibro-acoustic finite element (FE) model of the primary structure provided by Airbus Operations GmbH. The validation of the FE model is described by Wandel [4].

2.2.2. System Models

The system models for use in the noise estimation of the overall cabin design process are presented in this section. The models are completely modular and can be exchanged for higher (or lower) fidelity methods in the workflow anytime. Figure 3 gives

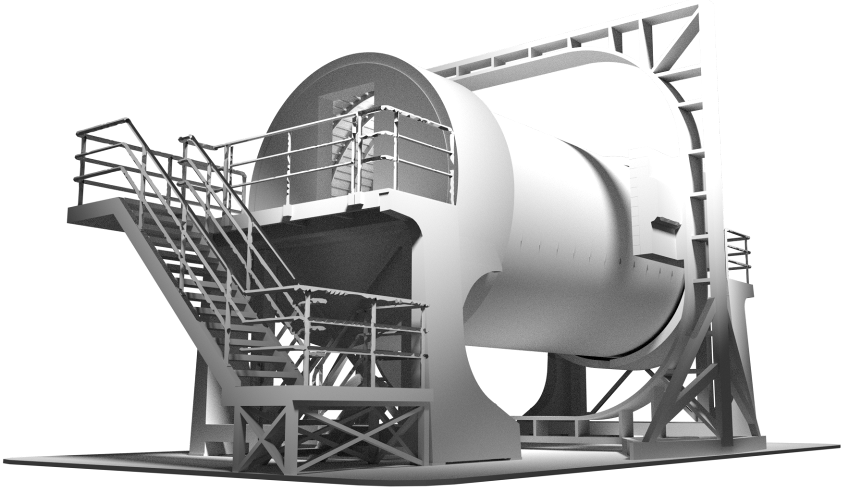

Figure 2: ACOUSTIC FLIGHT-LAB DEMONSTRATOR *in the testing environment*

a classification of the domains which are described by the system models on an aircraft level.

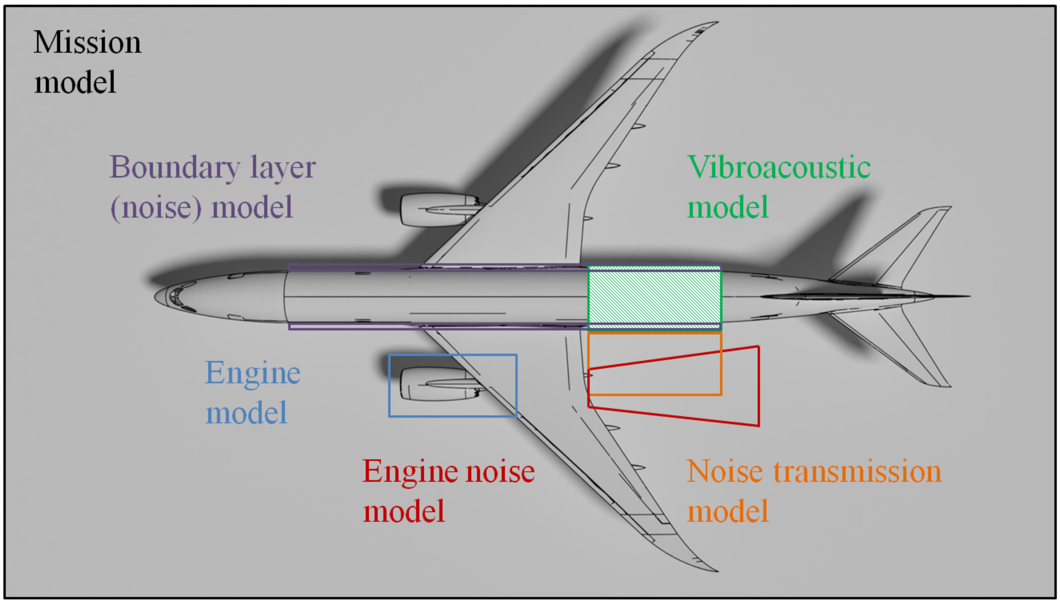

Figure 3: System models of the ACOUSTIC FLIGHT-LAB DEMONSTRATOR

An overview of the evaluation framework is given in Figure 4 in the form of an integrated RCE workflow. Each red block contains one system model and each line represents the exchange of data via an instance of the central data format. As a means of data exchange, the CPACS (Common Parametric Aircraft Configuration Schema) data format [5] developed at the German Aerospace Center (DLR) is used. CPACS is already an established standard for data exchange in collaborative aircraft design processes. It facilitates the integration of knowledge across disciplines, and also across level of detail ranging from simple empirical methods to computationally expensive high-fidelity methods. The detailed descriptions of each system model is given in the subsequent section.

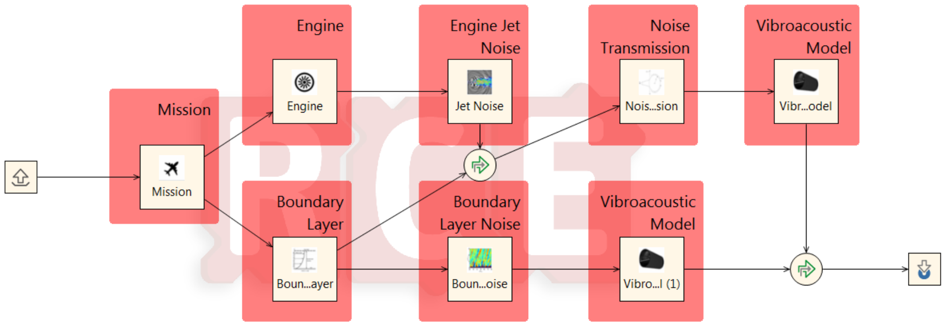

Figure 4: Integrated RCE workflow for cabin noise evaluation

Mission model The mission model describes the flight state of the aircraft at the design point. Only cruise conditions are considered in the context of this study. The parameters mach number, flight level and thrust are used as a basis for the succeeding noise prediction models. Also the properties of the exterior fluid, e.g. temperature, speed of sound, density, are evaluated at flight conditions and stored in the central data format.

Engine model In order to calculate the radiated noise from the aircraft engines, paramters of the engine design point in cruise conditions need to be known. Here, the predesign method by Bräunling [6, Sec. 6.12.2] is implemented to estimate the engine parameteres for generic turbojet and turbofan engines with a coaxial exhaust nozzle.

Engine noise model As a semi-empirical model for jet mixing noise of the engine, the methododology by Stone is used [7]. This describes the far-field sound pressure level of the radiated engine noise and characterizes the absolute noise level, spectral content in third-octave bands as well as source directivity. The spatial correlation of the radiated noise in the geometric near-field is approximated by utilizing a set of directional point sources placed at the centerline of the engine exhaust nozzle. The exhaust jet is divided into 3 source regions, i.e. the secondary-to-ambient shear layer, the interaction region and the mixed-flow region analog to [8]. These sources are designed in source strength to match the far-field results given by Stone.

Boundary layer All knowledge regarding the boundary layer is instantiated with this model. The turbulent boundary layer is itself a source of cabin noise. However, the influence of the boundary layer on exterior noise sources such as refraction and scattering is also well-known [9]. The thickness of the boundary layer is assessed by an empirical relation by Bies [10, Equation (*A*4)] and a quarter-sine mach number profile along the turbulent boundary layer thickness is assumed [9, Equation (6.3.5)].

Engine noise transmission This model describes the airborne noise transmission from the engine noise sources to the fuselage structure. The transmission path includes the convected free airstream down the fuselage, the refraction around the cylindrical structure as well as the scattering effect at the boundary layer. Here, the analytical monopole model by Gaffney [9] is implemented to model these effects. The method covers engine installations effects for a multitude of basic noise sources. It can furthermore be extended and applied to tonal spectral components, e.g. the engine fans, by the application of spinning disc sources.

Boundary layer noise The noise of the TBL impinging on the primary fuselage structure is assessed by the previously established boundary layer thickness. The auto-spectral density is evaluated with the model by Cockburn & Jolly [11]. The spacial correlation of the noise field is represented by the Corcos method [12]. These methods are used for evaluating statistical fluctuation parameters. The finite-element representation of the vibro-acoustic model however needs deterministic inputs for the evaluation of the cabin noise. For this coupling of statistical pressure fluctuations to the deterministic vibro-acoustic model the Cholesky approach [13] as well as the uncorrelated wall pressure plane waves method [14] are implemented. Both approaches have in common, that random phase angles are applied at each excitation realisation and in turn necessitates the repeated evaluation of the vibro-acoustic model as well as averaging over the multiple realisations.

Vibro-acoustic model The meshed geometry model for the structure and cavity is used for the solution of the coupled system of differential equations. Meshing and solving constitute the vibro-aboustic model of the components fuselage, interspace cavity, secondary structure as well as passenger cabin. A detailed description of the Acoustic Flight-LAB Demonstrator and the vibro-acoustic model is given in [3]. In order to get a global measure of sound radiation into the passenger cabin, the acoustic potential energy (APE) is used as a measure of acoustic comfort. It is equally possible to calculate the sound pressure at the passengers ear position, provided the seat positions are fixed and known.

The entire workflow is executed for different flight conditions and the results of the evaluation are given in the subsequent section.

3. EVALUATION RESULTS

This study adresses a framework for holistic evaluation of aircraft cabin noise in a multi-disciplinary context. A multitude of highly heterogenic tools with a variety of fidelity levels can be interconnected. Also, the evaluation framework can be individually tailored to suit the design process. Selected results with the incorporation of different of the aforementioned system models are given in this section.

3.3.1. Isolated engine

The first results are given by interconnection of the mission, engine as well as the engine noise model. This results in the isolated noise prediction for the jet exhaust mixing. The noise directivity of two engine configurations is shown in Figure 5 at a distance of 100 m. One generic type of a turbofan and a turbojet engine are assessed and the overall sound pressure level is plotted depending on the radiation angle. An angle of 0° depicts the flight direction. It becomes apparent that due to the higher exhaust velocities of the turbojet needed to create a comparable thrust than a turbofan engine, higher overall sound pressure levels are observed in the geometric far-field. The turbofan engine is used as a basis for cabin noise evaluation.

3.3.2. Installed engine

For the installed engine use-case, the additional boundary layer and noise transmission model are taken into account. This results in the near-field sound pressure values

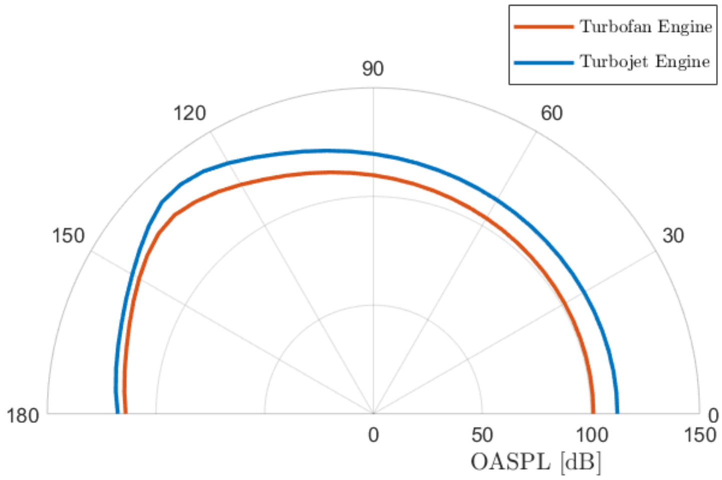

Figure 5: Overall sound pressure level directivity for different engine configurations (distance $r = 100\,m$)

impinging on the primary structure. This acoustic excitation contribution from the jet is generated by placing directional noise sources in the exhaust stream and appropriatly scaling them to match the aformentioned far-field levels of the isolated engine noise model. In the geometric near-field these sources are refracted and scattered by the turbulent boundary layer. In order to evaluate this shielding effect a measure

$$\triangle\mathrm{SPL} = \mathrm{SPL}_{bl} - \mathrm{SPL} \tag{1}$$

is introduced. Here, the quantity SPL_{bl} denotes the sound pressure level impinging on the outer hull of the primary structure including the boundary layer effect and SPL describes the solution of the convective wave equation alone. The latter one can be directly calculated with the noise transmission model by simply setting the boundary layer thickness to equal zero in the boundary layer model. Both solutions include the refraction effect along the cylinder circumference.

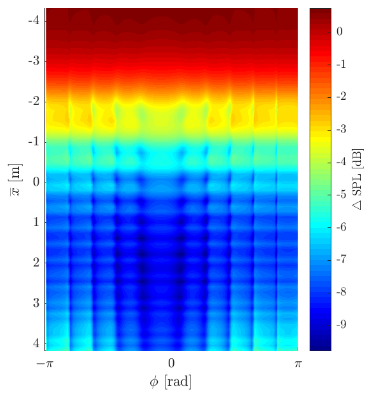

Figure 6: Sound pressure level difference due to shielding of a monopole source (Frequency $f = 350\,Hz$)

The sound pressure level difference $\triangle$SPL is given in Figure 6 on the unfurled fuselage structure. The centerline of the fuselage is indicated by $\phi = 0\,\mathrm{rad}$ and $\phi = \pi\,\mathrm{rad}$. The monopole source is placed at $\bar{x} = 0\,\mathrm{m}$, positive values for $\bar{x}$ mark the upstream direction. Negative values for the sound pressure level difference $\triangle$SPL indicate shielding by the turbulent boundary layer. Especially in the upstream region a substantial amount of shielding is observed which correlates well with [9, Figure 6.7]. The TBL refracts the waves towards the cylinder downstream of the source. The shielding effect downstream of the source is small compared to the upstream direction. The overall shielding effect is increased with rising frequency.

3.3.3. Vibroacoustic model

Through interconnection of the previously defined models for the noise sources with the vibroacoustic model, the cabin noise can be evaluated wholistically. Presented here are results for the installed jet as well as the boundary layer excitation. Also, a comparison of the evaluation process for different mission models is conducted.

Installed engine excitation The vibroacoustic model evaluation is conducted for the installed engine excitation. The acoustic pressure fluctuations exciting the primary fuselage structure are shown in Figure 7 on the left side at a discrete frequency. The excitation field is dominated by a multitude of point sources convected along the fuselage length and shielded by interaction with the boundary layer. The right side of Figure 7 plots the resulting vibrations from the primary structure in the normal direction. Additionally marked by the black dashed lines are the attachments of the cabin floor to the fuselage structure.

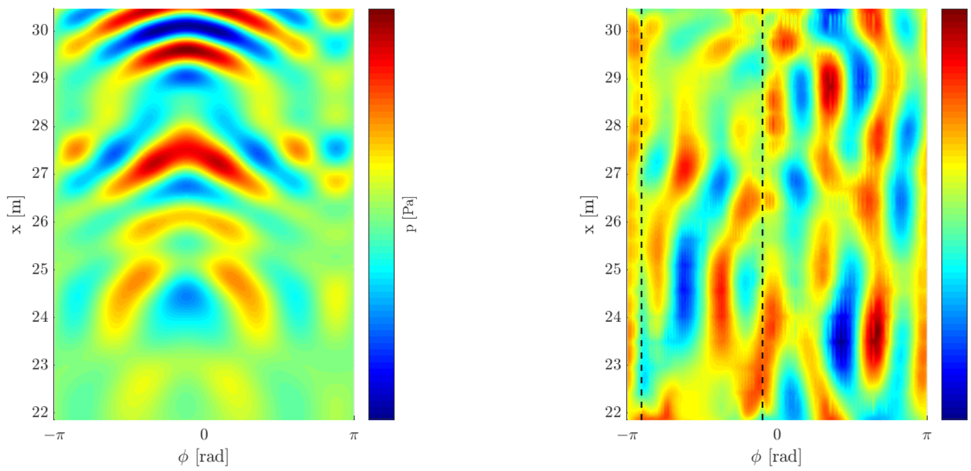

Figure 7: Acoustic pressure excitation (left) and resulting normal structural velocity fluctuations (right) on unfurled fuselage structure at $f = 125\,Hz$ due to installed jet excitation

Resulting from the jet noise excitation and the fuselage vibrations, the noise is transmitted over the airborne path (e.g. the insulation) and structure-borne path (e.g. shock mounts) to the secondary structure and radiates sound into the passenger cabin. Figure 8 plots the resulting acoustic pressure flucuations in the passenger cavity due to the aformentioned noise sources on the left side. The vibroacoustic model is examined regarding its transmission behaviour from the pressure fluctuations impinging on the primary structure to the acoustic pressure in the passenger cabin. In order to compare the noise transmission models for different sources, a transmission index $\Pi(\omega)$

$$\Pi(\omega) = 10\log_{10}\left(\frac{\frac{1}{N_e}\sum_{n_e=1}^{N_e}\left|p_{e,n_e}(\omega)\right|^2}{\frac{1}{N_i}\sum_{n_i=1}^{N_i}\left|p_{i,n_i}(\omega)\right|^2}\right) \tag{2}$$

is defined as the ratio of the mean interior to exterior absolute squared pressure. This transmission index is shown in Figure 8 on the left side for the installed jet excitation. The evaluated frequencies coincide with the respective line markers. The transmission index increases with frequency which indicates a higher susceptibility to the jet noise excitation at low frequencies. Further computations are necessary at a higher frequency resolution to derive the resonant contributions of the entire structural assembly as well as the acoustic transmission to the interior noise.

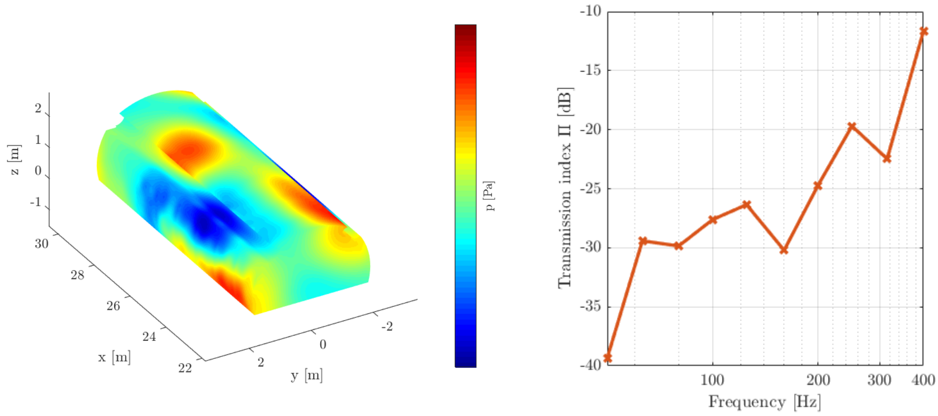

Figure 8: Acoustic pressure fluctuations in the passenger cabin at $f = 125\,Hz$ (left) and transmission index (right) for installed jet excitation

Boundary layer excitation For the evaluation of the cabin noise for the boundary layer excitation the mission, boundary layer as well as boundary layer noise are interconnected in order to generate the impinging sound pressure field. Analogously to the jet noise evaluation this excitation field is fed to the vibroacoustic model in order to compute the cabin noise. Figure 9 shows on the left side the pressure fluctuations on the fuselage skin. Clearly visible is the random spatial nature of the TBL noise. The normal structural velocity component of the primary fuselage structure excited by these exterior pressure fluctuations is plotted on the right side. Due to the random fluctuations of the boundary layer noise, many local skin field modes are excited on top of the global vibration modes.

Figure 10 plots the resulting acoustic pressure flucuations in the passenger cabin due to the aformentioned noise sources, plotted on the right side is the transmission index Π as defined in Equation 2.. It is clearly visible that despite the random nature of the exterior noise excitation, the resulting cabin noise has a large spatial correlation even for the TBL noise source model.

Influence of mission models In order to demonstrate a completely continuous and consistent data flow, the results for different mission models on the overall workflow

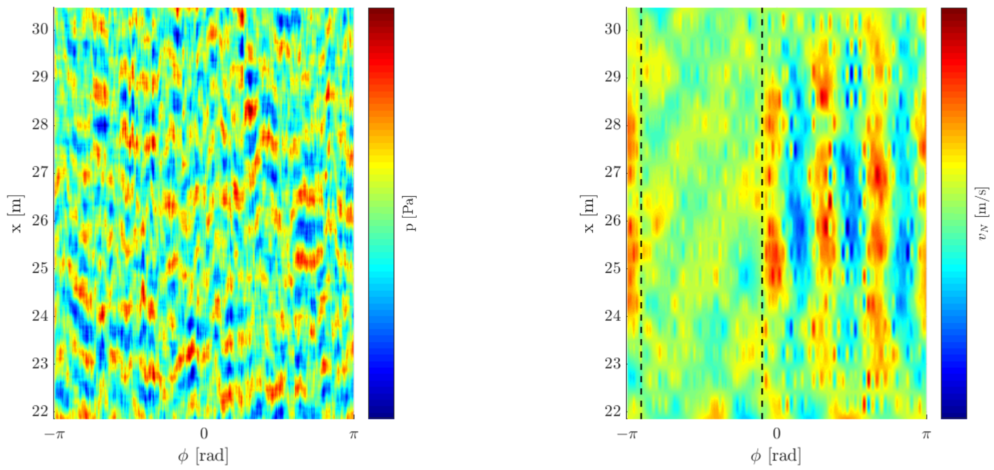

Figure 9: Acoustic pressure excitation (left) and resulting normal structural velocity fluctuations (right) on unfurled fuselage structure at f = 125 Hz due to boundary layer excitation

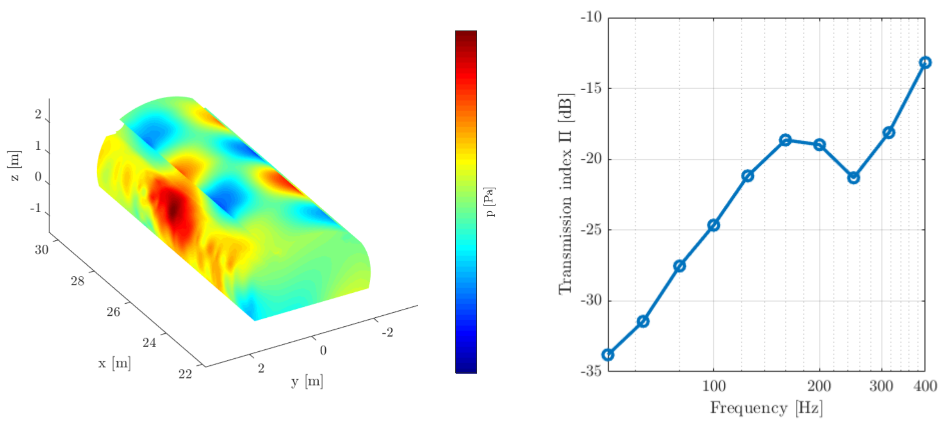

Figure 10: Acoustic pressure fluctuations in the passenger cabin at f = 125 Hz (left) and transmission index (right) for boundary layer excitation

are compared. They are fed to the boundary layer, boundary layer noise as well as the vibroacoustic model in order to compare the noise transmission into the passenger cabin for different flight conditions (i.e. flight level and machnumber). Figure 11 depicts the transmission index for two different cruise conditions calculated at identical frequencies. The maximum of difference amounts to about 8 dB at 25 Hz. The difference is anticipated to be much higher if the static loads due to the static pressure difference are considered which are highly dependent on the flight level. However, it is shown that the flight conditions need to be taken into consideration for realistic cabin noise predictions. Also, the framework for cabin noise evaluation is demonstrated to be consistent for different mission models and can be used as a basis for integrated optimizations.

4. CONCLUSION

This paper proposes a wholistic framework for the evaluation and optimization of aircraft cabin noise. The use of a model-centric data exchange enables a consistent

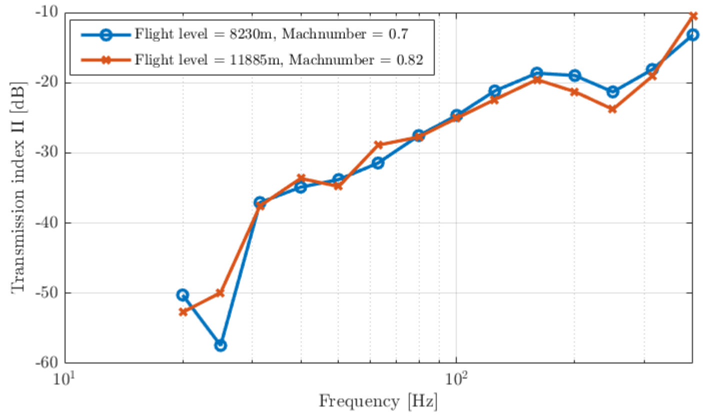

Figure 11: Comparison of transmission index for TBL noise at different mission states

integration of different system models into a fully automated workflow. The system models represent empirical, analytical and numerical evaluations of different disciplines which are usually executed by respective specialist of this field.

The approach facilitates the interlinkage of models with different levels of fidelity. The evaluation framework can be individually tailored to suit the desired design process. It is therefore fully flexible and each model is interchangeable with a different model of higher or lower fidelity. The targeted fidelity should be appropriate to the use-case and the design phase at hand.

Future work and research will be focused on the incorporation of additional system models and competences into the evaluation framework. Examples of models to be included are additional engine noise source like the fan tones from the secondary engine stage or the random shock cells in the supersonic exhaust stream. Also the inclusion and validation of vibroacoustic system models with physical prototypes for new technologies like windows, materials, insulation or seats will be of further interest.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to Airbus Operations GmbH and especially Dipl.-Ing. Martin Wandel, who supplied the FE model of the Acoustic Flight-LAB Demonstrator.

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