Influence of Different Turbulent Boundary Layer Criteria on Aircraft Cabin Noise

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Introduction

In order to meet set climate goals, the aviation sector has to face many challenges and undergo changes. Novel aircraft concepts are needed to tackle sustainability and energy efficiency in airborne-travel. However, these new aircraft concepts have to be accepted by the airlines and passengers. Here, not only affordability of flights, but also comfort plays a vital role. Gradually, the awareness for comfort while travelling is increasing meaning that it will play an important role in pushing new aircraft designs onto the general market. This comfort, however, does not only include seating but also noise. As Figure 1 suggests, passengers think of a flight as less satisfactory when the Sound Pressure Level (SPL) inside an aircraft cabin is higher. The above figure suggests that cabin noise has to be considered when developing new aircraft concepts, in order to increase technology acceptance. However, our goal is to push the consideration of acoustics into the holistic early design process, so that changes for an acoustically optimized design can happen early on with as low costs as possible. Therefore, the cabin noise has to be simulated with a vibroacoustic model. Cabin noise assessments are especially important to increase the technology acceptance of novel aircraft concepts that lately have been researched intensively, because the higher the comfort, the more likely people are to want to use such novel designs.

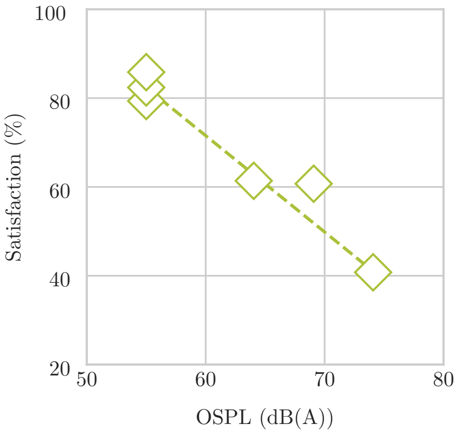

Figure 1: Satisfaction levels over SPL inside the aircraft cabin according to [10].

Simulation Set-Up

In order to gain valuable insights into the SPL distribution, we utilize high-fidelity models with wave-resolving methods. Here, the Finite-Element-Method (FEM) is used for simulating the SPL inside the aircraft cabin with our in-house code elementary Parallel Solver (elPaSo) [11], which is designed for high-efficiency frequency domain simulations. This allows us to compute the spatial SPL distribution in the whole aircraft in a frequency domain up to 1000 Hz. However, to further increase the efficiency of our simulations only a segment of an electrically propelled regional aircraft is considered in the following. The examined model is shown in Figure 2. Figure 2 shows an extruded view of the used model. The grey domain denotes the airframe, which is modelled by 9-noded shell elements. The outer skin is excited, which will be detailed in later sections and sound transmits into the red domain, which is the insulation, a porous medium modelled with equivalent fluid approach [2]. From there the sounds is transmitted into the interior trim denoted by the green domain. Again, 9-noded shell elements are used for the modelling. Lastly, the sound is radiated into the cabin volume, where the 27-noded fluid elements are used. Therefore, the SPL can be computed with this strongly coupled vibroacoustic model according to

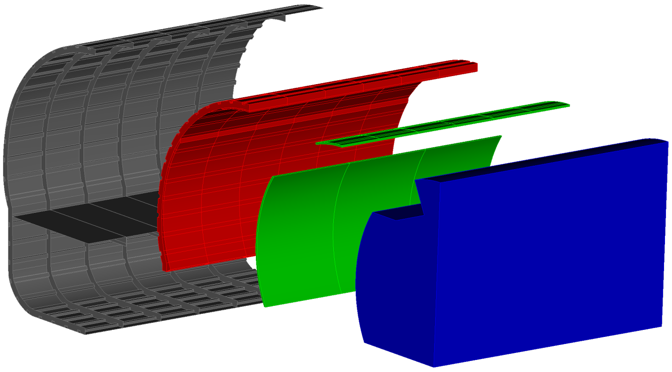

Figure 2: Extruded view of the examined FEM model.

$$(\mathbf{K} - \omega^2\mathbf{M})\mathbf{p} = \mathbf{F}, \qquad (1)$$

where **K** and **M** denote the stiffness and mass matrix, respectively. The angular frequency is given by ω. **p** is the vector of unknowns, while the right hand side **F** denotes the excitation. For this contribution we will focus on the excitation of the model.

Excitation

There many possible sound sources that can be the reason for cabin noise and for which a hybrid simulation chain was developed [1]. In this contribution the excitation of the outer skin due to the airflow around the aircraft is examined in further detail. Since the examined aircraft is an electrically driven propeller aircraft, there are two main noise sources regarding the airflow. The one arising from the propeller excitation and the one arising from the Turbulent Boundary Layer (TBL). This contribution will focus solely on the TBL excitation. The right hand side vector can be computed according to

$$\mathbf{F} = \int_{\Omega} p d\Omega, \tag{2}$$

where p is the pressure on the discretized element, meaning that the load is applied as elemental load. Therefore, in order to depict the excitation, the pressure has to be computed. This means, that the pressure underneath the TBL has to be computed, so that it can serve as input for the force vector assembly. A workflow that allows for the inclusion of the TBL as noise source has been presented in [5]. When referring to [5] the acquisition of data is still the same, however, for this contribution the computation of the pressure underneath the TBL is adapted. In the following the Uncorrelated Wall Plane Wave (UWPW) approach according to [7] is used. It states that the pressure underneath a TBL can be computed as a superposition of of plane waves described by

$$F(\mathbf{x}, \omega) = \sum_{h=1}^{N_x} \sum_{j=1}^{N_y} \sqrt{\frac{\Phi_{pp}(k_x, k_y, \omega) \partial k_y \partial k_y}{4\pi^2}} e^{i(k_x x + k_y y + \varphi_{hj})}, \tag{3}$$

where the exponential function describes a plane wave in axial (x) and circumferential (y) direction of the aircraft. It can also be seen that the TBL excitation is stochastic due to the random phase φ being added to the plane waves. Furthermore, the plane wave is weighted by the root term, namely

$$\phi_{pp}(\mathbf{k}, \omega) = \phi_{pp}(k_x, k_y, \omega) = \Psi_{pp}(\omega) \left(\frac{U_c}{\omega}\right)^2 \tilde{\phi}_{pp}(\mathbf{k}, \omega). \tag{4}$$

The wavenumbers in the respective main aircraft directions are denoted by k_i and U_c is the convective velocity. Again, two more factors are introduced, namely the cross spectrum density (CSD) $\tilde{\phi}_{pp}(\mathbf{k}, \omega)$ and the auto spectrum density function (ASD) $\Psi_{pp}(\omega)$. For both, many different semi-empirical models exist and literature is broad. We have implemented a variation of them, but for this contribution the ones validated in [6] are used. In [6] some models for the CSD and ASD computation are validated for the UWPW approach for a simple plate. Here, these models are adapted to generate pressure on the aircraft's outer skin as shown in Figure 2. The CSD is computed according to Mellen [8], which can be computed according to

$$\tilde{\phi}_{pp}(\mathbf{k}, \omega) = \frac{2\pi \left(\alpha_x \alpha_y\right)^2 k_c^3}{\left(\left(\alpha_x \alpha_y k_c\right)^2 \left(\alpha_x k_y\right)^2 \alpha_y^2 \left(k_x - k_c\right)^2\right)^{3/2}}. \tag{5}$$

Here, the wavenumbers play an important role, as well as the decay coefficients α, which can be set according to literature. For the ASD the classical Goody [3] model is used, which can be computed according to

$$\Psi_{pp}(\omega) = \frac{3\tau_W^2 \delta \xi^2}{U_e \left(\left(0.5 + \xi^{0.75}\right)^{3.7} + \left(1.1 R_T^{-0.57} \xi\right)^7\right)}, \tag{6}$$
$$\text{with} \quad \xi = \delta \frac{\omega}{U_e}, \quad R_T = \frac{U_\tau^2 \delta}{U_e \nu}.$$

It becomes obvious that the results from the RANS simulations can be used as a direct input for the computation of the CSD. The most important parameter in this model, which will be subject of later examination is δ, which denotes the TBL thickness. Meaning, that the TBL thickness plays an important role for the pressure underneath the TBL. This is the major difference in ASD models, as Goody is the only model that directly uses the TBL thickness to compute the CSD. With all these preparations it finally becomes possible to apply the UWPW approach to our aircraft and compute the pressure on the outer skin due to a TBL excitation and subsequently compute the SPL inside the aircraft cabin.

Influence of TBL Criteria

As mentioned in the previous section, the ASD model of Goody directly uses the TBL thickness δ as input for the computations. However, the TBL thickness cannot be computed directly and has to approximated with fluid data. There are different ways of approximating the TBL thickness, depending on the application and on the literature. [12], for example, gives a velocity criterion, which states that the TBL's edge is reached, when 99% of the free field velocity is reached. However, it is suggested that a 98% criterion can also be used. This means, that there is quite the discrepancy when it comes to approximating the TBL thickness. Additionally, sometimes not a velocity but a pressure based criterion is utilized, which suggests that the TBL's edge is reached when the total pressure is 99% of the free field pressure. Again, some variations can be found, that other percentages can be used for this criterion. This induces a direct variation in approximating the TBL thickness and thereby can directly influence the excitation of the aircraft. therefore, the question asked in this contribution is how sensitive is the SPL inside the aircraft cabin towards the approximation of the TBL thickness and does this sensitivity impact the SPL more than the variance of the TBL due to its stochastic nature. In the following section this question will be answered.

Results

In the following simulations of the model shown in Section are conducted with the excitation being computed with different TBL thickness criteria. The TBL excitation is increasing in a frequency range up to 1000-2000 Hz after which a drop-off occurs. Due to efficiency reasons, because many computations have to be evaluated, only frequencies up to 250 Hz will be considered here. Therefore, we are conducting a preliminary study. Furthermore, a variance band will be given for the computations to show the stochastic influence of the random phase of the UWPW approach. The following Table 1 shows the different TBL criteria used in the simulations. It becomes

Table 1: Evaluated TBL criteria for the simulations.

velocity-based	pressure-based
95%	95%
98%	98%
99%	99%

obvious that each criterion is evaluated with the standard 99% approach but to also showcase the sensitivity of the model towards the TBL thickness a somehwat unrealistic thickness approximation of 95% is chosen. Figure 3 depicts the comparison between the velocity-based criteria given in Table 1. It can be seen that there exists an offset between the three graphs, meaning that a thicker TBL (with increasing percentage, the TBL thickness increases) also leads to a generally larger SPL inside the aircraft cabin. The most prominent eigenfrequencies are depicted by all three graphs. Additionally, when keeping the variance band in mind it becomes obvious, that in lower frequencies, especially around 100 Hz, the influence of changing the criterion outweighs the stochastic nature of the TBL. In the higher examined frequency regime it can be seen that the v99 criterion differs from the other two, so here an distinction between the criteria has to be made. Generally, it can be said that the model seems to be sensitive with regards to the TBL thickness.

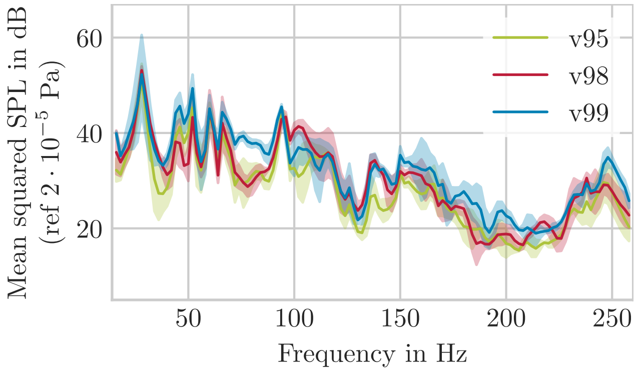

Figure 3: SPL inside the aircraft cabin for velocity-based TBL criteria. The number denotes the percentage of the free-field velocity, where we assume the TBL's edge is reached.

Table 1 also introduced pressure-based criteria that are examined in this contribution, which are depicted in Figure 4. Just like the previous figure, a clear offset between the different criteria can be seen. Again, with increasing TBL thickness (the higher the pressure criterion, the larger the TBL thickness) the SPL inside the cabin increases. The p95 criterion seems to lead to unrealistic results, since the offset to the other to is about 10 dB. Even when comparing the p95 to the v95 criterion of Figure 3 it can be seen that p95 seems to under approximate the TBL thickness. However, the p98 and p99 criteria are closer together, even though the offset still outweighs the stochastic nature of the TBL. Again, especially around 100 Hz this offset can clearly be seen in Figure 4. Generally, the TBL thickness seems to be more sensitive when using a pressure-based criterion, since the results significantly change between the different criteria. Therefore, the SPL also changes significantly with changing the TBL thickness approximation.

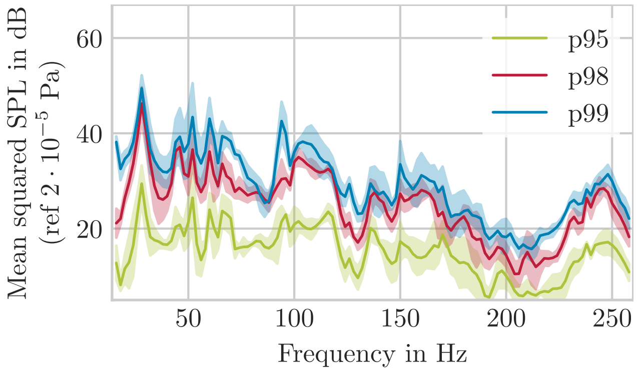

Figure 4: SPL inside the aircraft cabin for pressure-based TBL criteria. The number denotes the percentage of the free-field pressure, where we assume the TBL's edge is reached.

Lastly, a direct comparison between the pressure-based and velocity-based criteria has to be made. Since the 99% is the most prominent in literature the p99 and v99 criteria are directly compared in Figure 5. Again, some important observations can be made from the figure above. firstly, it seems that the velocity-based pressure criterion leads to larger TBL's since the SPL is higher for the v99 criterion than for the p99 criterion. The offset between both also outweighs the stochastic nature of the TBL, which means that the criteria are not interchangeable and the consideration of which criterion to use matters. Again, around 100 Hz the offset is the highest, while the most prominent eigenfrequencies are still met by both evaluations. Lastly, it can also be said that in between 100 Hz and 200 Hz the results are similar and it the stochastic variance is larger than the criteria variance. However, the general conclusion is still that one should study the used TBL thickness criterion when conducting simulations of SPLs for aircraft cabin noise. The SPL is sensitive with regards to the TBL's thickness.

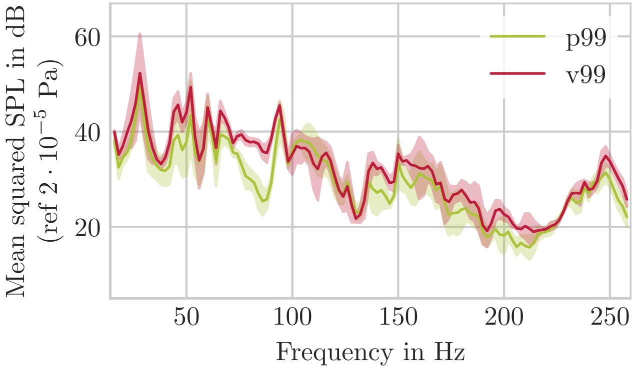

Figure 5: Comparison between velocity and pressure-based TBL criteria. Here, the TBL's thickness is assumed to be where velocity and pressure are 99% of the free field pressure/velocity, respectively.

Conclusion and Outlook

This contribution examined the influence of the approximation of the TBL's thickness has on the spatially averaged SPL inside an aircraft cabin excited by a TBL. All of the simulations presented have been computed with our in-house FEM code elPaSo [11] and the excitation has been included by computing the pressure underneath the TBL with the UWPW approach and the semi-empirical models of Goody and Mellen.

It has been shown that the SPL inside the aircraft cabin is quite sensitive with regards to the TBL thickness and changes quite significantly when the TBL thickness changes. The TBL thickness is needed in the model of Goody, but since it can only be approximated, the evaluation of different TBL criteria showed that they also significantly influence the TBL thickness and therefore the SPL levels inside the cabin. This means that the Goody model cannot be used for absolute comparisons of aircraft cabin noise, but only relative comparisons when the same TBL criterion is used. This contribution has shown that depending on which criterion is used the SPLs are not comparable at all since the results are quite different.

However, recent research has been looking for other ways to compute the ASD that does not include the approximation of the TBL's thickness in its formula. Examples are ASDs according to HU [4] and Rozenberg [9]. These models have been implemented by the authors. Here, instead of the TBL thickness, integral variables like the momentum thickness are used for the computation of the ASD. However, we are validating these models right now for our applicational case and they would eliminate the need to work with approximations and allow for an accurate evaluation of the ASD and therefore the pressure underneath a TBL. In the long run this should lead to better cabin noise predictions and a better comparability between results. In the future, this should also allow for an easier and more efficient noise assessment of different aircraft configurations.

Further research can focus on the examination of higher frequency domains as well as the efficient inclusion of many right hand sides. The TBL is stochastic and therefore many evaluations of the same model with different force vectors is needed for an accurate uncertainty quantification and therefore also an accurate noise assessment.

Acknowledgements

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