FULL-SCALE CABIN NOISE FROM TURBULENT BOUNDARY LAYER EXCITATION, PART 2: VIBROACOUSTIC MODELLING AND TRANSMISSION

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This paper is part of a two-fold study focused on the study of the cabin noise of a business jet conducted within the frame of the CANOBLE project of the EU's CleansSky2 program (Vibratec, Ecole Centrale de Lyon, GIE S2A, Dassault Aviation). The turbulent boundary layer developing on the fuselage is characterized by the wall pressure fluctuations that create an excitation that is transmitted and radiated inside the cabin, thereby contributing to a significant part of the noise during cruise. Many studies have looked into the properties and structures of wall pressure fluctuations beneath a turbulent boundary layer, nevertheless there is still a lack of knowledge of some of their components and of the effect of pressure gradients, even more on real geometries. This paper is focused on the implementation and validation of a numerical method to calculate structural vibrations and noise based on aerodynamic data from CFD simulations and from experimental data. The modelling strategy is first described. It involves a coupling between a hybrid structural/acoustic FEM model and a cross and auto power wall pressure spectra source generator. The source model includes heterogeneous boundary layer profiles and is fitted with experimental data conducted in a channel flow in the anechoic wind tunnel of Ecole Centrale de Lyon that served as a validation case. An application of the method with vibration and acoustics experimental data is performed at full-scale on a mockup of the fore part of a Dassault Aviation business jet in the GIE S2A industrial full scale wind tunnel going up to Mach 0.2 and 10 kHz.

Keywords: turbulent boundary layer, FEM, CFD, vibro-acoustic modelling.

1. Introduction and context

Considering the growth of the aviation sector in the future and its transition to a normal and common transport way, passenger's comfort needs will increasingly grow. One of the main demands is to have a quiet and low noise cabin. Turbulent Boundary Layers (TBL) are among main noise contributors since their important pressure fluctuations cause strong vibrations of the aircraft structure and thus noise radiation to the cabin. Considering the great computational effort to calculate unsteady pressure fields for large geometries, a variety of semi-empirical models has been developed over the last 60 years. The available semi-empirical models characterize the frequency dependence of the local pressure fluctuations (auto spectra) and the space-frequency dependence of the pressure field (cross spectra). In this paper, a vibroacoustic implementation applied to a realistic full scale fuselage aerostructure is discussed and compared with experimental data obtained in wind tunnel. Modelling strategy involves the CFD steady state calculation to predict the boundary layer profile, the prediction of the turbulent wall pressure fluctuation (TWPF) excitations and the structural and acoustic response. The paper is structured in the following order: Section 2 presents the modelling strategy applied to a full scale aerostructure. Section 3 is dedicated to the boundary layer profile prediction. Section 4 is dedicated to the prediction of the TWPF excitation. Section 5 is devoted to the vibroacoustic response. Numerical results are compared with experimental aerodynamic, vibration and acoustic data acquired during extensive wind tunnel sessions conducted at full scale [1].

2. Modelling Strategy applied to a full scale cockpit & cabin aircraft

In this part, the wall pressure fluctuations $p(\mathbf{x}, t)$ are determined based on calculations of auto and cross spectra. Firstly, a RANS simulation is done on the geometry of interest. Then, the aerodynamic parameters of interest are extracted in order to calculate the auto and cross spectra of the wall pressure based on semi-empirical models. Finally, a sampling approach in the space/frequency domain is used in order to compute the response of the structure subject to the load given by the cross Power Spectral Density matrix. The whole strategy can be seen in Figure 1.

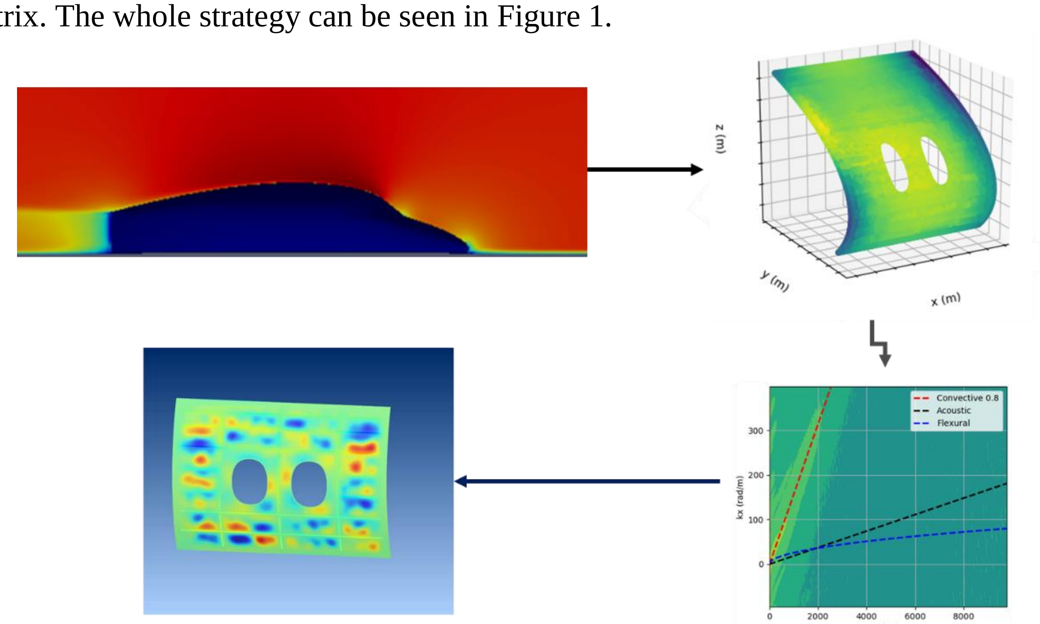

Figure 1: Computational process overview

The proposed implementation has been successfully validated with measurement on a flat plate submitted to a uniform turbulent boundary layer [2].

The modelling strategy is applied on a realistic cockpit & cabin aircraft mockup.

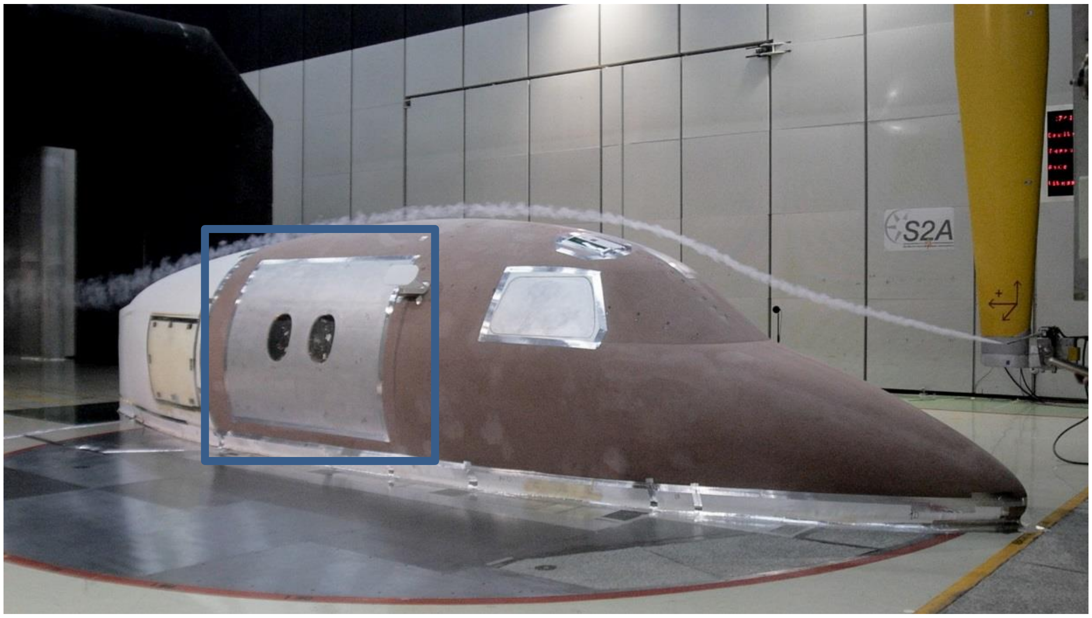

Figure 2: View of the full scale cockpit & cabin mockup

The computational process described in Section 2 is applied in a four-step approach. First, the velocity profile is predicted using RANS CFD calculation, then the boundary layer profile is extracted. In a third step, the TBL cross-spectrum matrix is computed and loaded on the vibroacoustic model.

The panel of interest is a realistic aerostructure made of stringer and frames clamped with rivets on a skin fuselage.

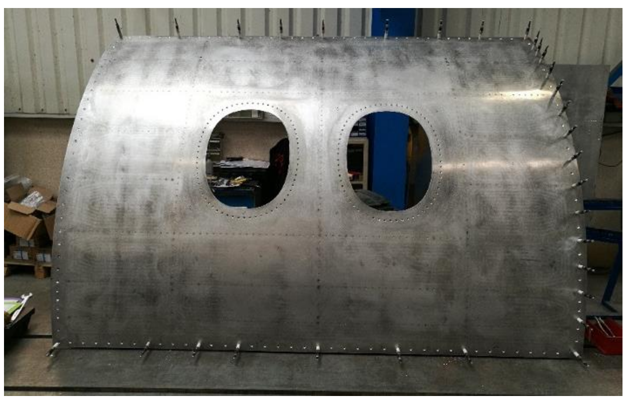

Figure 3 : View of the aerostructure panel

The panel radiates inside an inner trimmed cavity. To only measure and model the vibration and noise due to the TBL loading on the panel, the aerostructure is mounted on dampers to isolate the structural part of interest with the rest of the mockup profile.

3. CFD analysis and boundary layer profile extraction

To predict the boundary layer profile along the aerostructure, an incompressible steady-state kw-SST RANS model is built.

Number of cells	75M
Y+	30
Turbulence	kω-SST
Inlet Velocity BC	45 m/s or 65 m/s

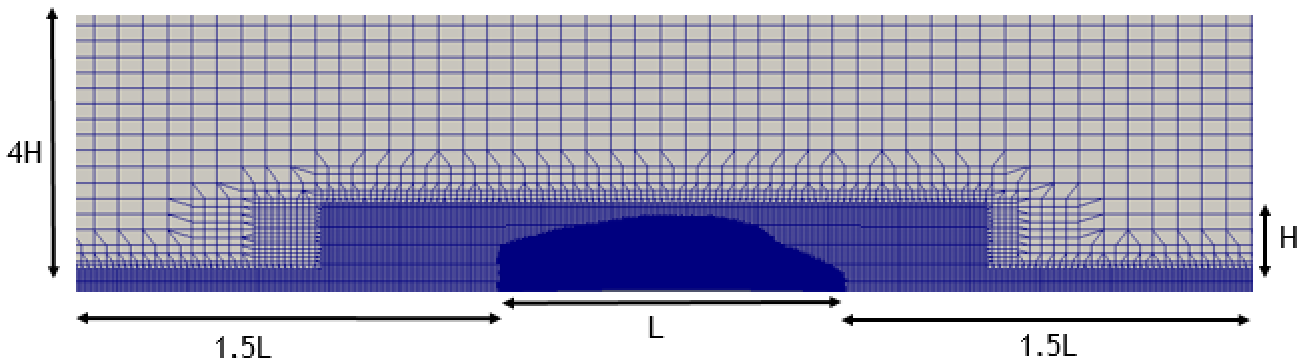

Figure 4 : longitudinal cut-plane of the CFD domain

The CFD analysis is validated by comparison of the numerical and experimental pressure coefficients along longitudinal and azimuthal streamlines.

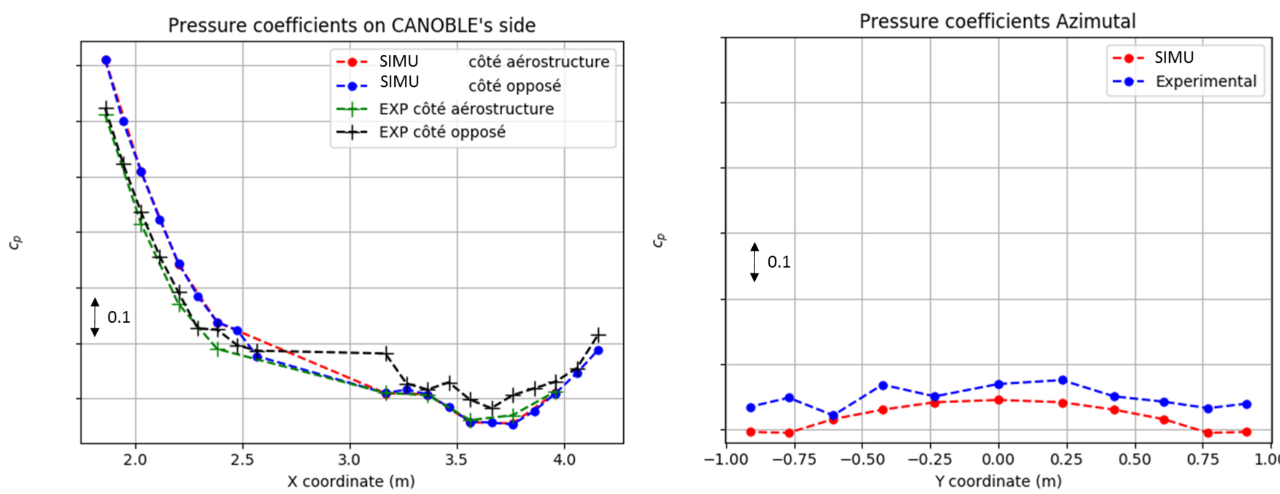

Figure 5: Numerical and experimental pressure coefficients

Then, the turbulent boundary layer profile is extracted along the panel. For validation purpose, the predicted boundary layer profile is compared with hot wire measurements conducted at one point upstream the panel.

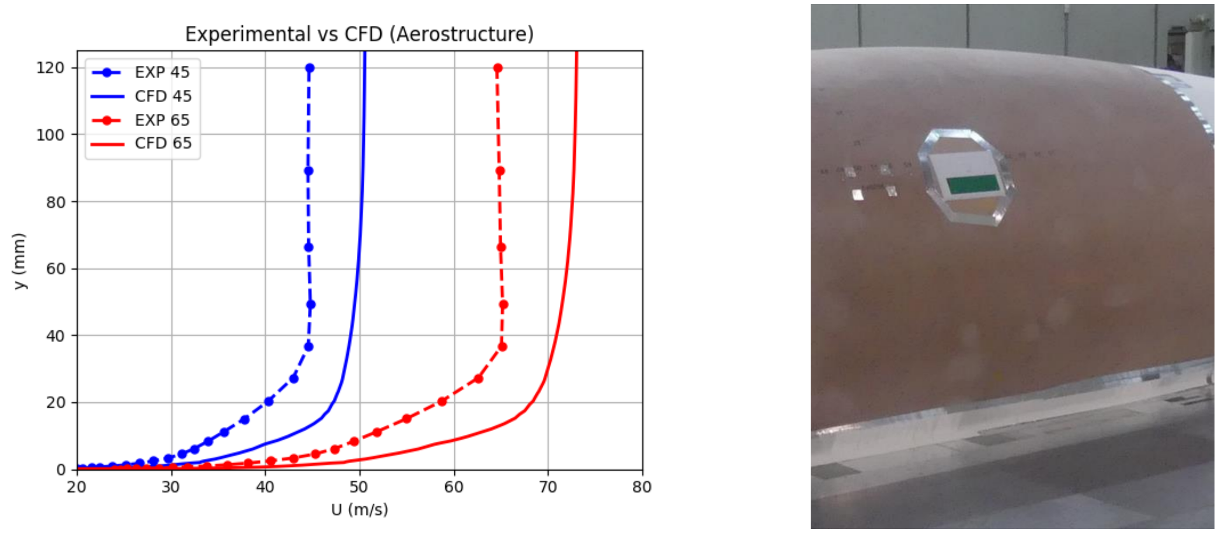

Figure 6: Numerical and experimental boundary layer profile extraction

The BL profile is correctly extracted. It is observed that the freestream velocity is overestimated by the simulation. It could be further improved by adjusting the velocity inlet boundary condition.

Finally, essential BL profile quantities are extracted and interpolated along the aerostructure:

- τ_w the wall shear stress [Pa] extracted from the velocity profile (deduced from the friction velocity
- U_e the freestream velocity [m/s]
- δ_1 the boundary layer displacement thickness [m]

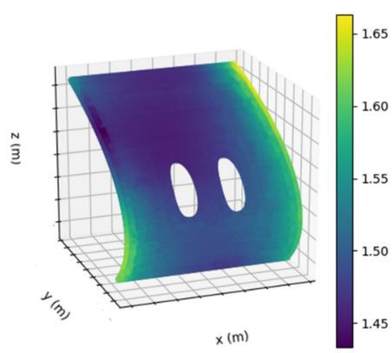

Figure 7: Friction velocity projected on the aerostructure @45m/s

A comparison with test data validates the good prediction of those quantities.

	Ue [m/s]	δ_1 [mm]	Utau [m/s]
EXP	64,6	5,86	2,55
NUM	73,1	5,53	2,12

Tableau 1 : BL profile quantities – Experimental / Predicted comparison

4. Turbulent Boundary Layer Excitation

From the BL profile, various quantities are extracted. The $R(\xi_1, \xi_2, \omega)$ cross-correlation power spectral density (PSD) matrix is a combination of the $\phi(\omega)$ auto-power reference spectrum given here by Goody's model and the $S_n(\xi_1, \xi_2, \omega)$ spatial correlation matrix calculated here using Corcos' model.

Auto-Power / Goody's model	Spatial correlation // Corcos'model
$\phi(\omega) = \frac{(\tau\omega)^2}{U_e} \frac{C_2\left(\frac{\omega\delta}{U_e}\right)^2}{\left[\left(\frac{\omega\delta}{U_e}\right)^{0.75} + 1\right]^{3.7} + \left[C_3\left(\frac{\omega\delta}{U_e}\right)\right]^7}$	$S_n(\xi_1, \xi_2, \omega) = e^{-\left\lvert\frac{\xi_1}{L_1}\right\rvert} e^{-\left\lvert\frac{\xi_2}{L_2}\right\rvert} e^{-i\omega\frac{\xi_1}{U_c}}$
PSD Matrix $R(\xi_1, \xi_2, \omega) = \phi(\omega) S_n(\xi_1, \xi_2, \omega)$	

The excitation is first compared with the experimental data. The LMFA data (cyan curve) is the measured auto-power. Heterogeneous data (red curve) is the predicted auto-power when using CFD data. Finally Homogeneous data (dot blue) is the predicted auto-power using the experimental data. The proposed TWPF source model is able to reproduce both trends and level. To be noticed that the peack around 20 kHz of the measured auto-power is due to the sensor resonance and it can be easily removed using a frequency calibration process.

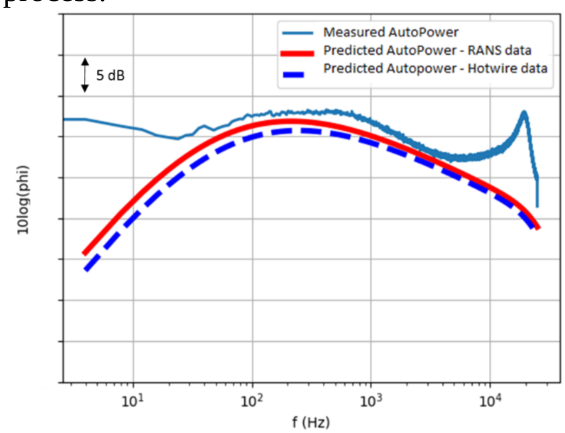

Figure 8: Measured and computed auto-power

Finally, the wavenumber frequency spectra is computed and applied on the external skin of the aero-structure panel.

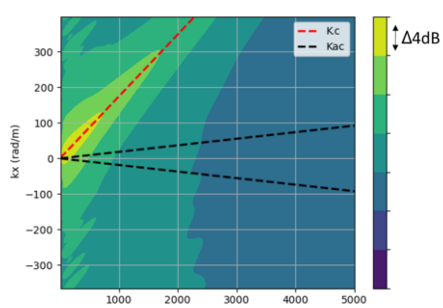

Figure 9: Computed Wavenumber-frequency diagram for U0 = 45m.s−1

5. Vibroacoustic response

The corresponding FEM vibroacoustic model is made of two main components:

- The structural part characterized by its structural modes with a 1% structural damping,
- An acoustic inner cavity.

A weak modal/physics vibroacoustic coupling is applied at the pressure/displacement interface.

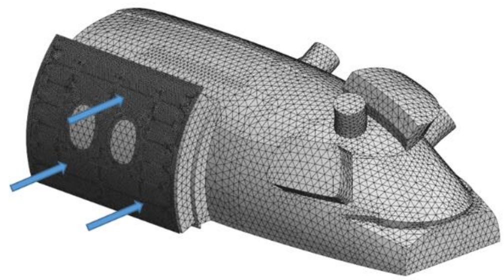

Figure 10: Vibroacoustic FEM model

A first validation of the structural model is conducted by comparison with measured Frequency Response Functions (Figure 11). The acceleration of the structure is in good agreement up to 1 kHz. The panel mobility is slightly underestimated around 400Hz.

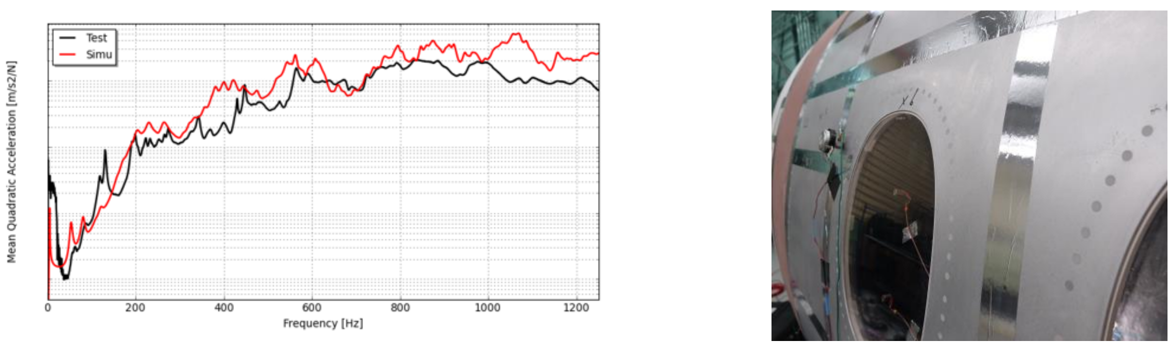

Figure 11: Predicted & Measured mean quadratic acceleration under point load excitation

A second validation is conducted when applying a diffuse sound field (DSF) excitation (Figure 12). The transmission loss is compared with the experimental data. Above 1 kHz, the measured transmission loss is decreasing. A deeper analysis must be conducted.

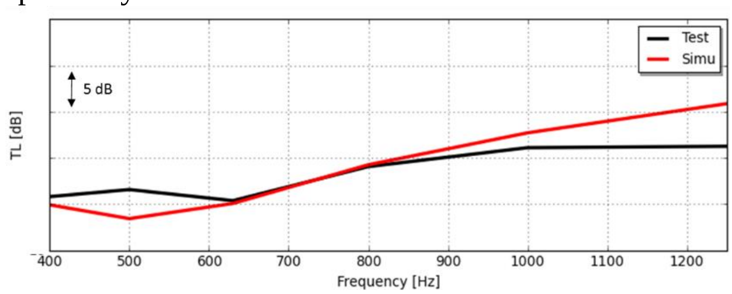

Figure 12: Predicted & Measured Transmission Loss under DSF excitation

Finally, the TWPF excitation is loaded on the panel. Both vibrations of the panel and radiated noise inside the cabin are predicted. A comparison with the test data is presented in Figure 13.

Figure 13: Radiated power and pressure map in dB inside the cabin @45 m/s

6. Conclusions

In the frame of the CANOBLE Cleansky2 program, a new vibroacoustic strategy to address cockpit and cabin interior noise has been developed and compared to an extensive experimental data base. Based on standard semi-empirical model extended to heterogeneous boundary layer profiles extracted from RANS CFD data, the vibroacoustic response induced by the turbulent boundary layer excitation can be predicted. This implementation opens new opportunities from the integration of more complex semi-empirical model extracted from the test and the extension to higher Mach number. This work has been conducted under the CANOBLE Cleansky2 project (JTI-CS2-2015-CFP02-LPA-01-05, project id 717084).

References

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