CABIN NOISE FROM BOUNDARY LAYER EXCITATION: FULL-SCALE WALL-PRESSURE MEASUREMENT AND VIBROACOUSTICS TRANSMISSION

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This paper is focused on the study of the interior cabin noise of a commercial jet conducted within the frame of the CANOBLE project of the EU's CleansSky2 program. From the development of key technologies to measure the Turbulent Wall Pressure Fluctuation excitation (TWPF) and to predict the interior noise by transmission through the fuselage, a test campaign has been conducted in the S2A wind tunnel to measure the aero-vibroacoustics transmission on a mock-up of the fore part of a Dassault Aviation business jet.

The paper will first present the technologies developed in the frame of the project with the introduction of a advanced pressure sensors to measure the wall pressure excitation and a numerical workflow to predict the interior noise. The second and third parts will be focused on the presentation of the full-scale wind tunnel test campaign and the analysis of the results. Various configurations will be discussed.

This research has been funded by the European Union through the CANOBLE Cleansky project (H2020-CS2-CFP02-2015-01, project id 717084),

Keywords: turbulent boundary layer, wall pressure, MEMs advanced sensor, wind tunnel test, 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, passengers and pilot 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 inside the cabin.

The turbulent boundary layer developing on the fuselage creates excitation through a wall pressure fluctuations that are, to some extent, transmitted and radiated inside the cabin, 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, however there is still a lack of knowledge for some of their components and on the effect of pressure gradients, more so on realistic geometries. When dealing pressure wall in an industrial context, new constrains also occur. The complexity of the geometry and the associated flow field, the intrusive properties of the instrumentation, the size of the samples and at least the overall cost.

To tackle these current limitations, the CANOLE (2016-2019) aims to address, by test and simulation, the characterization of the wall pressure excitation and the transmission in a vibroacoustics context using new key technologies affordable in an industrial context. The paper is an overview of the main achievements starting, in Part 1, with the experimental approach and, in Part 2, with the modelling approach.

2. Experimental and Numerical key technologies

2.1 Digital wall pressure array for wall pressure measurements

Previous studies have looked into the possibility to measure wavenumber- frequency spectra of wall pressure fluctuations with a rotating line array of remote microphones [1, 2, 3, 4]. The antenna's rotation and the remote approach provide an increased number of separation vectors in the physical space. In its current state, this technology requires back access through the studied wall, and is only suited to a laboratory wind tunnel where a wall can be fitted with such a system. On the other hand, the recent development of acoustic array [5, 6] based on the MEMs technology opens new opportunities. Indeed, the sensor size combines two interesting features with the possibility to a use high density of flush mounted pressure sensor keeping a very low thickness of the array, a major requirement to be non-intrusive.

In the present study, the authors choose to implement INMP621 digital microphones, commercialized by InvenSense. That microphone has small dimensions – 4×3×1 mm^3 –, and does not require any front-end acquisition setup, thanks to its digital output. Each antenna is composed of 40 digital microphones, non-uniformly distributed on a cross whose main axis is aligned with the flow direction. The present antenna is thus based on the array presented by Salze et al. [7]. The distribution of the microphones on the board is illustrated in Figure 1.

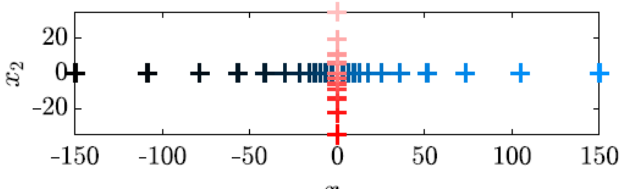


Figure 1 : Positions of the corresponding microphones on the board

The array had first been consolidated on a dedicated test bed, Figure 2, developed at LMFA laboratory, to validate the response and results with reference instrumentation. The wave-number decomposition process allow to extract the acoustic contribution and the hydrodynamic features of the wall-pressure fluctuations.

Fig4

Figure 2 : At left: Closed wind tunnel at Centre Acoustique, École Centrale de Lyon. At right: MEMS array with digital microphones, stuck onto the wind tunnel surface.

2.2 Vibroacoustics transmission modelling under TBL excitation

Considering the great computational effort to calculate unsteady pressure fields for large geometries, a variety of semi-empirical models has been developed. 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). The cross-correlation power spectral density (PSD) matrix is then the result of the multiplication of the reference spectrum and the spatial correlation matrix:

$$\text{�}(\xi_1, \xi_2, \omega) = \phi(\omega)\text{�}_n(\xi_1, \xi_2, \omega)$$

The single-point wall pressure frequency spectra of Goody’s model [2] is given by:

$$\phi(\omega) = \frac{\frac{(\tau\omega)^2}{U_e} C_2 \left(\frac{\omega}{e}\right)^2}{\left[\left(\frac{\omega\delta}{U_e}\right)^{0.75}_2 + 1\right]^{3.7} + \left[C_3 \left(\frac{\omega\delta}{U_e}\right)\right]_7}$$

Where, $C_1 = 0.5$, $C_2 = 3.0$, $C_3 = 1.1 * \text{�}^{0.57}$ and $\text{�} = \frac{\delta \quad u_\tau}{\text{�}_e \quad \text{�}}$ is the ratio of outer and inner boundary layer time scales. The space/frequency spectra of Goody’s [3] model is given by:

$$\text{�}(\xi_1, \xi_2, \omega) = e^{-\frac{|\text{�}|}{L_1} - \frac{|\text{�}|}{L_2} - i\omega\frac{\text{�}}{\text{�}}}$$

Where $L_1 = \frac{\text{�}_c}{\text{�}}$ is the coherence length in the streamwise direction and $L_2 = \frac{\text{�}}{\text{�}}$ is the coherence length in the crosswise direction. It is based on the assumption that both directions are independent. Experimental observations lead to $\text{�} = 0.1$ and

$\text{�} = 0.77$.

These semi-empirical models allow a fast and reliable way of calculating the auto and cross spectra based on the mean properties of the flow. The selected aero-vibroacoustics modelling strategy, detailed in [8] is implemented in way to support a TBL excitation enhanced with stationary non-uniform data coming from BL profile measurement or CFD data. An additional extension of the implementation allow the direct exploitation of the measured test spectrum.

The proposed implementation has been first compared with test data conducted on the closed wind tunnel test bed where a vibroacoustic flat plate has been instrumented [9].

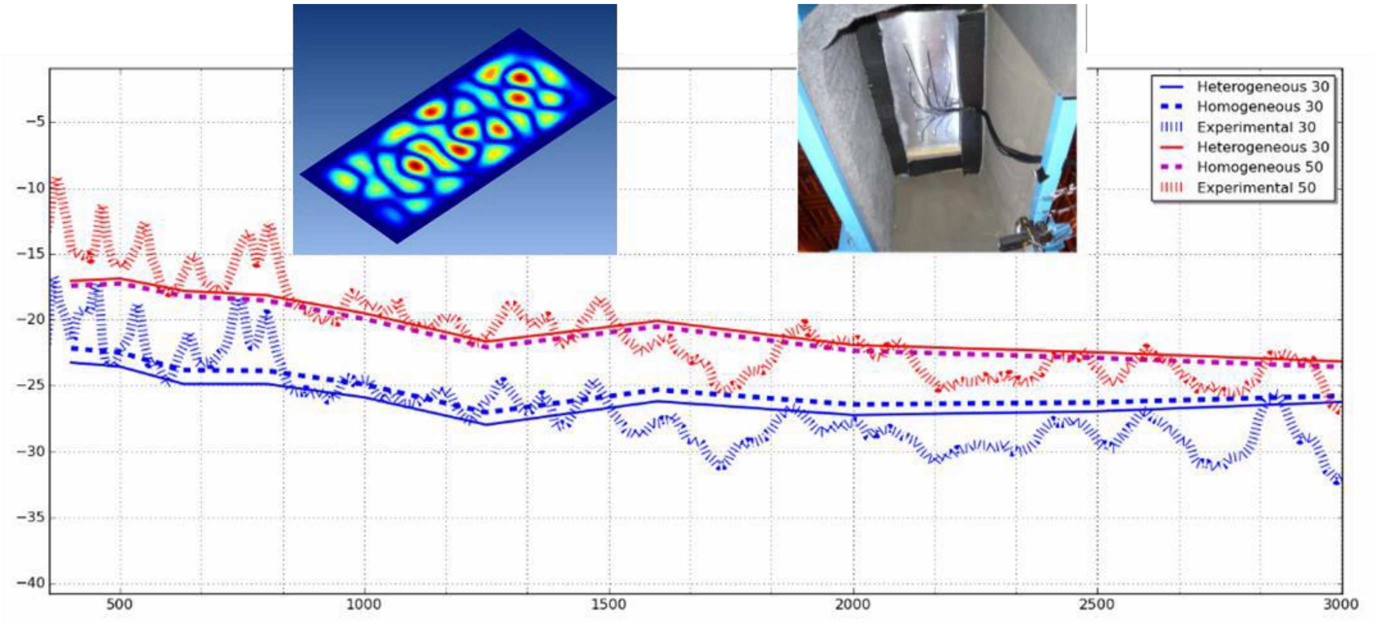


Figure 3 : Accelerations at the center of the plate. Comparison between the experimental data and the vibroacoustic model with a homogeneous TBL and an heterogeneous TBL exictiation for Ux=30m/s, Ux=50m/s

2.3 Wind-tunnel and mock-up

Measurements are conducted in the S2A industrial aeroacoustics wind tunnel near Paris, France. The closed-loop tunnel opens to a test room with an inlet section of 24m2. Results presented in this paper have been measured with outer velocities ranging from 15 to 65 m.s-1.

The mock-up (Figure 4) used in this study is a full-scale fore part of a Dassault Aviation business jet. The mock-up is 10m long in total, with the first 6m true to the aeroplane geometry, and the remainder serving as a tail to streamline the rear end.

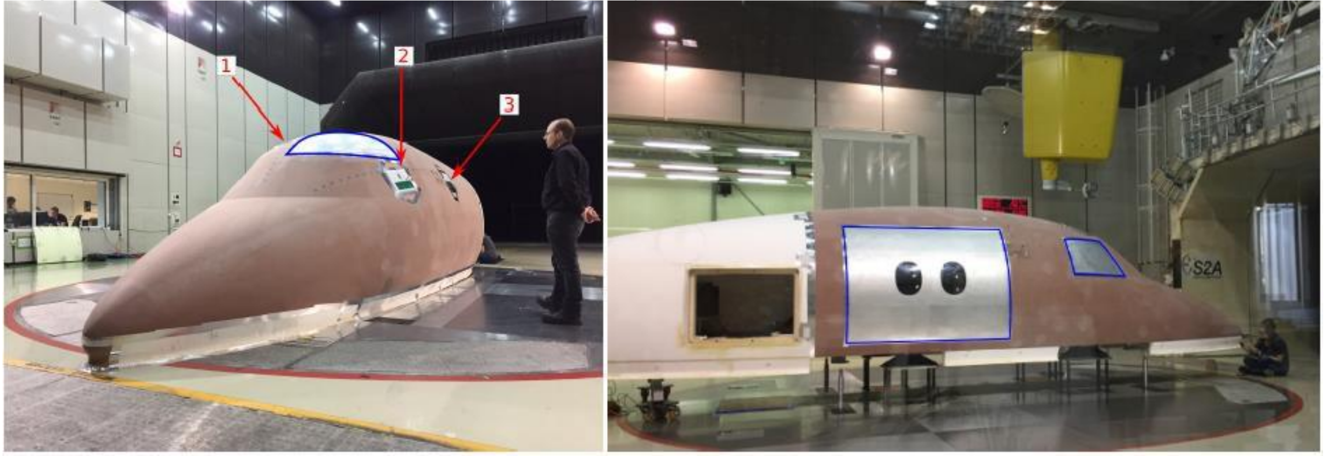


Figure 4 : Mock-up installed in the wind tunnel.

The outer surface was milled to the geometry while static pressure sensors were fitted along some specific streamlines and two kinds of inserts were added. Final instrumentation (Figure 5) is made of:

- Panels mimicking the vibrational behaviour of a real jet fuselage were added to the structure, and were equipped with accelerometers to study noise radiation.
- External modules supporting wall pressure microphone antennas, hot films, hot wires and other devices were placed in locations mirroring those of the panels. Those three modules correspond, respectively, to the roof, windscreen and side panel.

- Interior acoustic cavity for interior noise measurements (interior acoustic array, intensity probes and microphones).

Figure 5 : View of the instrumented Mock-up / Wall pressure surface array (left), instrumented vibration panels (middle) and interior noise cavity (right)

3. Results and exploitation at full scale

3.1 Boundary layer measurement and wall pressure spectra

The modules supporting the antenna were fitted with a reference microphone and a hot film, and enabled a traverse to be installed for hot-wire measurements. The boundary layer was thus characterized for each target velocity and the friction velocities obtained from fitted profiles were satisfactorily checked against those directly measured with hot films. The mean velocity profiles, normalised by wall units and obtained for the three modules, are shown in Figure 6 for three representative outer velocities: 30, 45 and 65 m.s−1.

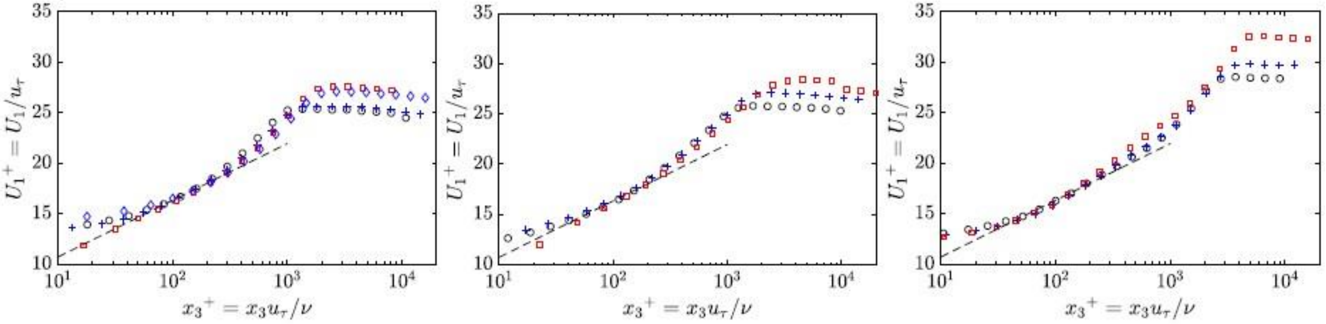


Figure 6 : Mean profiles in wall units for the three modules, ordered from left to right, at 30 (circles), 45 (pluses) and 65 m.s–1 (squares). Extra velocity for module 1 at 70 m.s–1 (diamonds).

The boundary layers from modules 1 (cap) and 2 (windshield) exhibit very similar profiles, reaching almost the same values and starting their plateau at the same normalised distance from the wall. On the other hand, the profiles from module 3 (side panel) reach higher values of normalized velocity and the logarithmic region is more developed.

In addition, 64 static pressure (P) probes were placed alongside streamlines that had been selected to cross the measurements location, to directly measure the local pressure gradient. The non-dimensional pressure gradient parameter for the three modules at 30 m.s^{-1} are 0.03, −0.15 and 0.08, respectively. At 45 m.s−1, the same parameters are 0.053, −0.22 and 0.11, respectively. This indicates that the boundary layer over module 1 is subjected to an almost-zero pressure gradient, the one over module 2 to a favourable pressure gradient, and the one over module 3 to a mild adverse one.

By the Fourier transform of the spatio-temporal correlation function, the 1D wavenumber-frequency spectra for various velocities is extracted. Results for module 3 (side panel) is illustrated in Figure 7. The convective ridge is clearly visible on the maps, however, no acoustic component can be found. Some artefacts are visible at low frequencies, up to 500 Hz for the highest velocities that are most likely due to the discretisation of the antenna.

Apart from this aspect, the maps are overall clearly measured and it confirms despite the difficulties added by this realistic geometry, the matured technology has proven reliable.

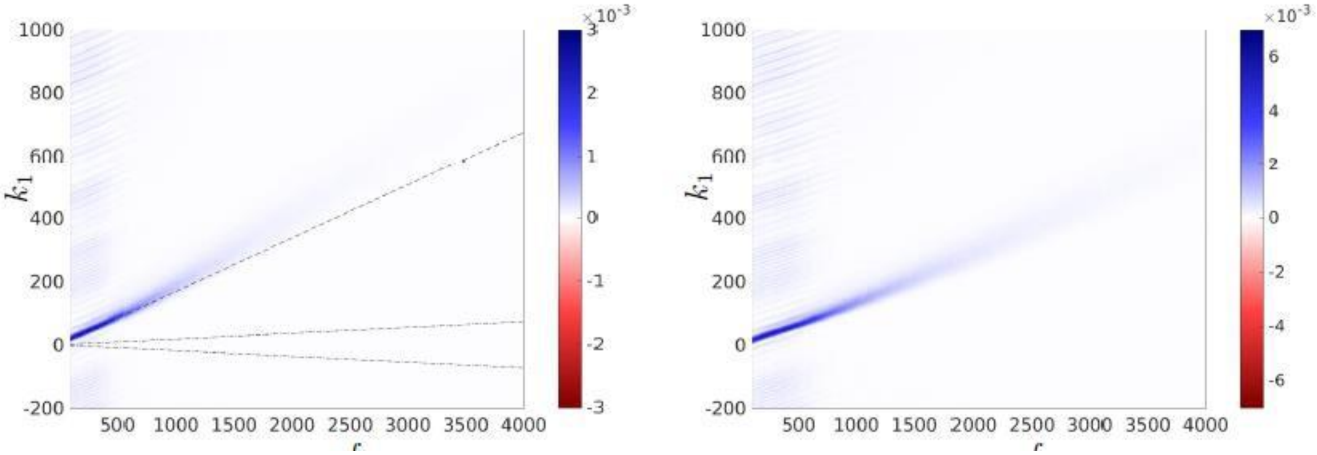


Figure 7 : Stream-wise wavenumber-frequency spectra for 45 and 60 m.s−1.

Further detailed on measurement in available in [10]

3.2 Aero-Vibroacoustics Prediction

The modelling process applied at full scale is illustrated in Figure 8 and fully described in [11]. Starting from RANS simulation, boundary layer profile are extracted. PSD-Matrix is then generated and loaded on a structural model coupled to an acoustic

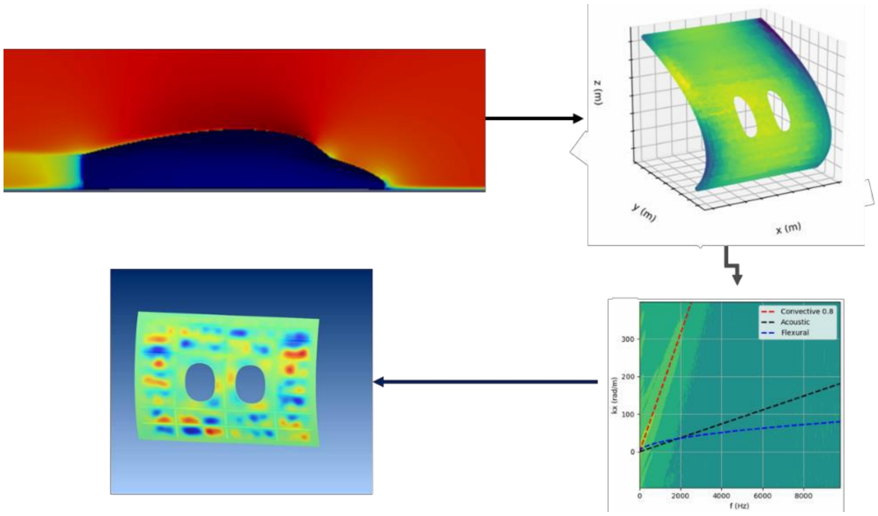
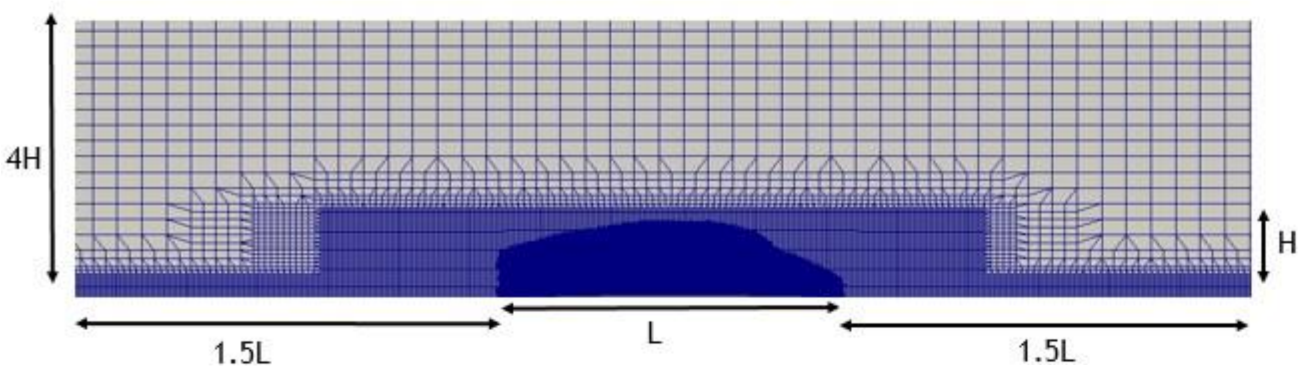


Figure 8: Computational process overview

The CFD analysis is validated by comparison of the numerical and experimental pressure coefficients along longitudinal and azimuthal streamlines (Figure 9).



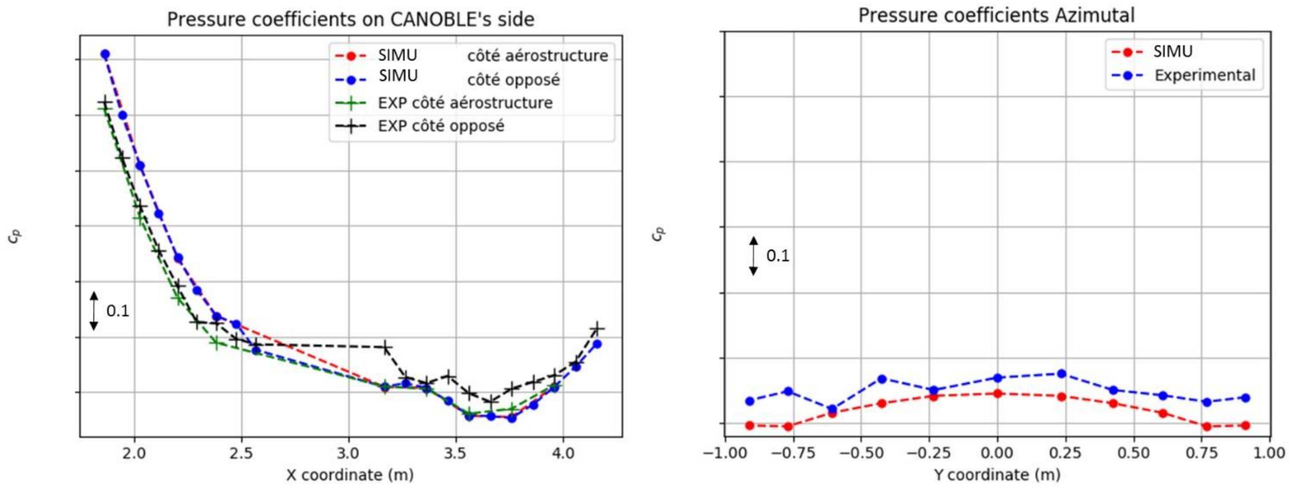


Figure 9: Numerical and experimental pressure coefficients

Essential BL profile quantities are then 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]

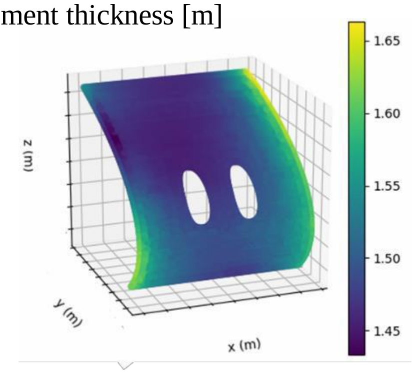


Figure 10: Friction velocity projected on the aerostructure @45m/s

The wavenumber frequency spectra is computed and applied on the external skin of the aerostructure panel (Figure 11).

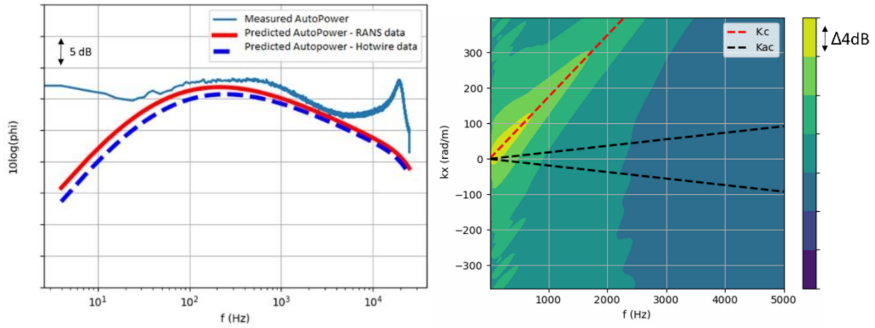


Figure 11: Auto-Power and Computed Stream-wise Wavenumber-frequency diagram for U0 = 45m.s−1

The Auto-power spectra is computed in two different ways, using predicted BL profile or directly using hot-wire measurement data. In the two cases, results are in agreement with the experimental data. On the wave-number spectra, the convective ridge is clearly visible on the maps.

In a last step, the interior noise is predicted by transmission allowing to estimate the acoustic field inside the cavity as well as the radiated power generated by the structural sample. A comparison with measurement data done with intensity probes are illustrated in Figure 12.

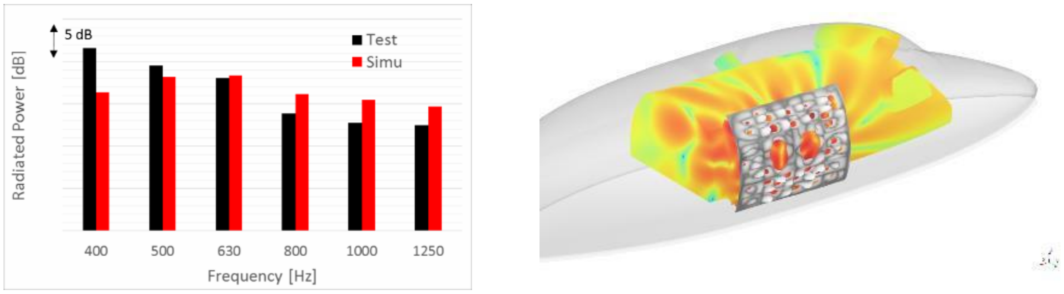


Figure 12: Radiated power and pressure map in dB inside the cabin @45 m/s

Overall noise acoustic power level is in line with the measurements. In the 400Hz band, prediction level are under-estimated, a phenomena mainly explained by the modal behaviour of the structural samples which differs between the simulation and the test. To notice that most of the acoustic energy is in the 500-1000 Hz band, frequency range where the sub-structure of the panel start to be mechanically excited.

4. Conclusions

To address interior noise due to the TBL, a full-scale mock-up of a cockpit and cabin section has been instrumented and tested in a large aeroacoustics wind tunnel. Through the development and the validation of innovative key test and simulation technologies, major experimental and numerical data bases, including for all physics aerodynamics, unsteady wall pressure, vibration and acoustics have been produced for various low Mach number conditions in different pressure gradient conditions. Providing access to design methods for a low-noise and low-mass cockpit and cabin signifies a major step forward opening new opportunities for flight measurement and for designing future low-noise cockpit and cabin.

Acknowledgement

This research has been funded by the European Union through the CANOBLE Cleansky project (H2020-CS2-CFP02-2015-01, project id 717084).

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