



# Aircraft and technology for low noise short take-off and landing

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This paper discusses characteristic multi-disciplinary issues related to quiet short takeoff and landing for civil transport aircraft with a typical short to medium range mission. The work reported here is focussing on the noise aspects and is embedded in the collaborative research centre CRC880 in Braunschweig, Germany. This long term aircraft research initiative focusses on a new transport aircraft segment for operation on airports with shorter runway length in commercial air transport. This calls for a community-friendly aircraft designed for operations much closer to the home of its passengers than today. This scenario sets challenging, seemingly contradictory aircraft technology requirements, namely those for extreme lift augmentation at low noise. The Research Centre CRC880 has therefore devised a range of technology projects that aim at significant noise reductions and at the generation of efficient and flexible high lift. The research also addresses flight dynamics of aircraft at takeoff and landing. Two companion papers, reporting about the research in the field of "Efficient high lift"<sup>1</sup> and "Flight dynamics"<sup>2</sup> complete the presentation of the CRC880. It is envisaged that in general significant noise reduction -compared to a reference turbofan driven aircraft of year 2000 technology- necessarily requires component noise reduction in combination with a low noise a/c concept. Results are presented from all the acoustics related projects of CRC880 which cover the aeroacoustic simulation of the source noise reduction by flow permeable materials, the characterization, development, manufacturing and operation of (porous) materials especially tailored to aeroacoustics, new UHBR turbofan arrangements for minimum exterior noise due to acoustic shielding as well as the prediction of jet noise vibration excitation of cabin noise by UHBR engines compared to conventional turbofans at cruise.

## I. Introduction

The mobility needs of industrialized countries have generated significant growth in aviation, bringing the air transport system closer to its limits. Aviation adds significantly to CO2 emissions, perceived noise and land usage of the developed industrial countries, and the used airspace has increased up to capacity limitations in some areas. These issues are reflected in the "Vision Flightpath 2050 – Strategic Research and Innovation Agenda".<sup>4</sup> According to these long-term objectives of the major European aviation stakeholders, new technological approaches can only be successful if they address simultaneously environment protection, drastic energy savings, improved flight safety, and reductions in door-to-door travel times.

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A more detailed analysis of technologies for future commercial transport reveals the strong impact that the high-lift system of the aircraft has on the aircraft operating cost, the usage of carbon-based fuels, aircraft emissions, and flight safety. Multi-element high lift systems in use on present aircraft have a multitude of effects on aircraft performance. While their manufacture and maintenance affect aircraft operation cost, the capabilities of these systems to generate lift allow overall wing design for optimum cruise efficiency and enable aircraft service to a prescribed class of airport infrastructures. However, present high lift systems exhibit limited flexibility to extend their performance once wing sizing and detailed design of the leading edge and trailing edge devices for take-off and landing have been defined. This leaves little design options to adapt high-lift performance later on, i.e. to growing aircraft weight or to configuration changes such as the installation of alternate engines with larger diameters. Furthermore, the need for conventional leading edge devices such as slats or Kruger presents a severe difficulty in the introduction of laminar flow on the wing, as envisaged for significant cruise drag reductions. Finally, conventional high-lift devices are a major source of airframe noise of current aircraft. Note that the performance of the high lift system also determines the air speed at takeoff and approach conditions and affects all sources of airframe noise, as these sources scale with the 5th to 6th power of flow speed.

The Collaborative Research Centre CRC 880 located in Braunschweig, Germany, combines the competencies of Technische Universität Braunschweig, Leibniz Universität Hannover and the German Aerospace Center, DLR, for fundamental and applied research in high lift of future commercial aircraft. The overall working hypothesis of the Research Centre CRC 880 states that active high lift systems with high levels of aerodynamic efficiency add significant value to future civil transport. These active systems can provide higher flexibility in the generation of high lift for aircraft families and aircraft upgrades, allow significant reductions of airframe noise emissions, and finally provide a technically feasible and economically viable path towards short takeoff and landing capabilities. The latter route of research aims at a new transport aircraft segment for operation on airports with shorter runway length presently not considered in commercial air transport.<sup>5</sup>

New aircraft of this segment would be equipped with advanced technologies for drastic airframe and engine noise reduction. They would represent a community-friendly aircraft designed for operations much closer to the home of passengers than possible today, operating effectively in point-to-point services between metropolitan areas. The Research Centre CRC 880 has therefore devised a range of technology projects, aiming at drastic noise reductions and at the generation of efficient and flexible high lift. The research also addresses flight dynamics of aircraft at takeoff and landing. Technology assessment plays an integrated part in coordinating the Research Centre. For this purpose, a reference aircraft configuration is defined using fully iterated preliminary aircraft designs. The reference configuration represents the state of the art in CO2 reductions, low noise, and STOL for efficient point-to-point service. The reference aircraft allows assessing the individual impact that the various research projects on aeroacoustics, aerodynamics, advanced wing materials and structures, and aircraft flight mechanics have. While detailed research objectives and the general layout of the CRC 880 research areas was presented in Ref.,<sup>6</sup> the present status of the center's research is the subject of three overviews presented at the AIAA conference, i.e. this contribution along with,<sup>1,2</sup>

The ACARE acknowledges that restricting R&T to single a/c components will furtherly not suffice to meet the objective of -10dB per aircraft operation in 2020 as set out by the strategic paper "Vision 2020" of the EU in 2001. In addition, these so called 1st and 2nd generation noise reduction technologies have to be considered in combination with low noise aircraft architectures.<sup>3</sup> This is even more valid for the longer term view, described in the above mentioned document Flightpath 2050 of ACARE.<sup>4</sup> In view of noise, another aspect of the development of transport aircraft is of concern, which is driven by fuel savings and environmental requirements. This aspect concerns the increase in size of the aeroengines of modern conventional aircraft: one will see classical sources of noise diminish, while new sources, related to the close integration of engines and wing, will occur. Consequently, according to<sup>7</sup> one of three requirements of ACARE on future noise research is to very significantly increase the effort dedicated to Low Noise Aircraft configurations.

## II. Overview about aircraft configuration and related technologies

For the current funding period of CRC880 an over-the-wing nacelle turbofan propulsion arrangement was chosen. A configuration with promissing engine installation efficiency was taken as the basis, characterized by the engine intake located at about the wing trailing edge position.<sup>8</sup> This basic aircraft configuration,



Figure 1: CRC880 concept transport aircraft for quiet STOL properties REF3.

depicted in figure 1, is of particular importance for several reasons. The chosen engine location allows enough space for highly efficient extreme high bypass ratio turbofans (BPR $\geq 15$ ) with the consequence of very low jet noise. The main engine source remaining for such engine is fan noise. In fact, since the intake length-to-diameter ratio is smaller than at conventional turbofans and the frequencies are lower, the intake liner effectiveness for the absorption of fan forward noise would typically represent a serious issue. However, the engine arrangement provides a significant noise shielding potential for the sound radiated out of the intake of the engine. Moreover, contrary to conventional under-the-wing arrangements of the nacelle, fan rearward sound does not experience any ground-ward reflection at the wing-flap geometry, which therefore reduces the installed fan rearward noise on the order of 3dB. Moreover, liners in the duct downstream of the fan can potentially be arranged as particularly efficient absorbers. Detailed research on advanced liner technology for this purpose was deliberately omitted in this project since considerable progress in this field is expected in the near-to-mid term future as a result of research of other expert groups. The considered engine integration also avoids any jet-flap-interference noise potentially occuring for closely coupled UHBR under the wing configurations.

As far as airframe noise is concerned, research in CRC880 is not focussed on undercarriage noise reduction because very significant noise reduction solutions have already been developed in the past in the course of various European research projects like SILENCER and TIMPAN. The use of these practically available low noise gears is implicitly assumed. However, it is particularly noted that again as part of the integration of the main landing gear in the pylons of the engine nacelles as sketched in fig 1, any installation noise source due to the landing gear wake-flap interference is avoided by design. This seemingly small configurational detail may be highly important, since the wake-flap installation source would occur at conventional aircraft and limit the effectiveness of any low noise gears because the source would occur independent of whether the landing gear as such was or was not a silent design. Another positive configurational feature of the considered aircraft concept on undercarriage noise is the fact that the landing gear is equipped with short legs, simplifying the design of low noise solutions.

One key element of the considered aircraft configuration is rather the high lift system because it represents on the one hand the enabler for the short take-off and landing requirement. On the other hand, the noise of conventional high lift systems remains the most difficult issue of airframe noise. For this reason a considerable research effort in CRC880 is devoted to this problem. An active high lift system is considered, which consists of a non-slotted flap with a tangential flow control jet to keep the flap flow attached by means of the Coanda effect in combination with a droop nose at the wing leading edge to provide for the necessary lift at low speed conditions. This high lift concept was chosen because by design it avoids slots, the flow through which is known to generate most of the noise in conventional high lift systems along with the complex track system for slats and flaps.

In order to turn this a/c concept into a realistic solution for a low noise aircaft with short take-off and landing capabilities eight key research areas have been identified, directly and indirectly relating to the noise issue. Figure 2 gives an overview about these key research areas. Because of the key role of these areas related in-depth research is done in respective sub projects; these are discussed in the following sections.



Figure 2: Overview about research activities in CRC880 on aircraft noise.

## III. Detailed low noise aircraft technologies

This section is devoted to the research areas needed to overcome the most critical technological challenges in relation to the quiet short take-off and landing requirement.

## 1. Engine integration of low noise aircraft configuration (sub project A3)

While the basic configuration was obviously chosen to provoke fan forward noise shielding by the wing, there are several difficult problems to be solved concering the aerodynamic viability of the aircraft and the engine integration in particular.

The main focus of the partial project A3 is the integration of the propulsion system of the STOL aircraft with respect to the aerodynamic and aeroacoustic performance. For the numerical studies on the aerodynamic behavior both a reference aircraft and engine model are required. The chosen configuration features a low wing design, with a T-tail and UHBR turbofan engines mounted over the wing at the trailing edge. This design has already proved to provide many advantages in terms of decrease of the runway length needed for take-off and landing and of noise reduction, but it potentially may also present many problems due to the increase of the interference drag at high speed conditions. The short take-off and landing capabilities together with the low noise characteristics are essential in order to fulfill one of the long term aims of commercial aviation: to make operational those airports which are currently not usable due to their small size or their proximity to residential areas. Previous researches<sup>8</sup> prove, however, that the interference phenomena for an over-the-wing mounted engine can be favorable and produce a reduction of the drag with respect to a conventional under-the-wing engine configuration due to the interaction of the engine flow with the upper wing shock. This is the main motivation of this study: the investigation of the aerodynamic phenomena related to the installation of the UHBR engine on the wing with respect to different flight conditions and engine positions. Two approaches for installing the propulsion system are investigated. The first configuration will be a pylon-mounted engine while the second one is a highly integrated wing/engine configuration obtained by embedding the nacelle into the wing. In addition to the aerodynamic sensitivity analysis on both configurations an aeroacoustic assessment in terms of noise emission is also part of this sub project as well as the investigation on the interaction of an over-the-wing mounted engine with the aircraft's active high lift system.

#### Aerodynamics

For the aerodynamic studies a steady 3D RANS approach is used and the simulations are run with the



**Figure 3:** First results of the integration studies of the podded engines for cruise flight conditions, see.<sup>9</sup>

DLR flow solver TAU-Code.<sup>11</sup> For the integration studies a surface model of the aircrafts Wing-Body (WB) and UHBR engine are required, which were created with the commercial CAD tool CATIA V5. The clean aircraft and isolated nacelle simulation results are needed as a reference for the following studies. As mentioned above the aircraft features a low wing with a sweep angle of  $26^{\circ}$  and a corresponding twist distribution, which was already used during the first funding period of CRC880 and proved to fit best for this test case. On the propulsion side there is the thermodynamic cycle of the UHBR-engine based on the aircraft flight envelope which delivers relevant dimensions as an input for the surface model generation. The model is fully parameterized to easily implement changes either due to updates in the basic geometry requirements coming from the thermodynamic cycle of the engine or caused by the aerodynamic characteristics of the engine model. For the nacelle, the upper and lower profile can be adapted separately to fit both high speed and low speed requirements. The hybrid meshes were generated with the commercial tool CENTAUR from CentaurSoft. To ensure mesh independent results studies on the mesh settings have been carried out. The grid sizes are around 9 Mio. nodes for the WB, 5 Mio nodes for the isolated engine and 13 Mio nodes for the Wing-Body-Engine (WBE). Particular attention has been dedicated to the generation of the mesh for the engine inflow and outflow planes: the grid uniformity in those regions is essential in order to let TAU properly apply the engine boundary conditions and compute the engine flow. For the isolated engine steady RANS simulations in three operating points (TakeOff, Cruise and Top of Climb) were conducted. The boundary conditions were taken from the engine design. While at the fan face a constant massflow condition was applied, the bypass and core nozzle exits of the engine were realized by a pressure and temperature ratio relative to the farfield state. In order to evaluate the interference effect of the pylonmounted configuration due to the engine only, the WBE (no pylon) configuration is being studied and



Figure 4: Skin friction lines on WB (left) and WBE (right) for podded engine. The engine is omitted to the aim of clarity.



Figure 5: Fully integrated UHBR engine. Left: first design variant, right: pressure coefficient and influence of installation.

compared to the wing-body only. The CFD simulations are run with a 3D RANS approach and with the Spalart-Allmaras (SA) turbulence model in its negative version. On the other hand, first versions of the embedded configuration are tested as well using the Shear Stress Transport (SST) turbulence model. Specifically conducted simulations for studying the influence of different turbulence models have shown a negligible effect on the results comparing SA and SST. Since the first phase of the study is focused on the high speed performances only, the simulations are run for the Start of Cruise test case, with Ma = 0.78 at target  $c_L = 0.46$  and with powered engine.

For the integration studies a generic UHBR-engine model was developed which meets the thrust requirements in the respective mission points of the aircraft. This engine setup represents the baseline for further aerodynamic and aeroacoustic investigations. In figure 3 the pressure contour on the WB (picture on the left side) is compared to the one on the WBE (picture at the center and on the right side), with the engine mounted at the spanwise reference position  $\eta = 0.31$ . First results of the integration studies show that the installation of a turbofan engine over the wing has a positive effect on the shock location on the upper wing surface, since the shock is clearly moving upstream in the section where the engine is located. Therefore, a significant potential is seen in using the engine aerodynamic installation effects to improve drag for this reference configuration.

Furthermore, figure 4 depicts the skin friction lines on the wing's surface for both WB and WBE configuration. The positive effect of the engine integration at the reference vertical position  $Z_{ref}$  in the mitigation of the trailing edge separation occurring on the WB is clearly visible.

First aerodynamic results for the fully integrated arrangements are shown in figure 5. Note that in this case the nacelle is slightly shifted upstream compared to the podded engine installation so that the fan face is positioned at the trailing edge of the wing. The installation of the engine leads to a shift of the main shock location upstream and abreast to the engine intake as well as a reduction of the shock strength. The streamlines also indicate that the flow separates on the engine nacelle surface as it can be seen in the right image of figure 5.

Positioning studies on both configurations are being carried out, investigating the transonic flow phenomena and the interference effects derived from a variation of the position of the engine in vertical direction. Figure 6 shows the pressure diagrams for two cuts along the wing's span, at  $\eta = 0.31$  and  $\eta = 0.66$  and for two vertical positions of the engine. The engine has been shifted first closer to the wing's surface (at  $Z_A = 0.8 \cdot Z_{ref}$ ) and then further away from it (at  $Z_B = 1.2 \cdot Z_{ref}$ ). In order to better investigate the aerodynamic background, these simulations have been run for a target angle of attack equal to the one obtained from the WB computations at target lift coefficient. With the decrease of the angle of attack the shock is completely supressed in the region where the engine is installed, and it tends to move instead towards the outboard part of the wing. At  $\eta = 0.66$ , due to the interaction of the engine flow with the wing flow, the shock tends to become weaker with respect to the WB configuration and to move towards the trailing edge by around 4 % local chord length. No relevant differences can be seen for the different engine positions, except for different flow accelerations due to the different gaps between engine lower surface and wing upper surface.

Again in order to better investigate the aerodynamic phenomena for the fully integrated configuration, simulations have been carried out for a fixed angle of attack at  $\alpha = 2.4$ , which was obtained from the WB computations at target lift coefficient. As it can be seen on the left hand side of figure 7 a decrease in the angle of attack leads to a full suppression of the shock upstream of the engine position. The shock on the wings upper side also becomes weaker in direction towards the wing tip (right figure) analogously as for the podded case.

The main current objective is to provide a drag breakdown into physical components in order to identify and select those configurations with the engine position corresponding to the minimum installation drag at fixed lift coefficient. Furthermore, the potential of the aerodynamic impact of the landing gear casing on the flow phenomena will be investigated. The positioning study of the engine will be continued in the next phases of the project, by shifting the engine in Z-wise and X-wise direction, in order to explore different scenarios of the installation effects. The different positions of the engine will be then analyzed and compared in terms of overall drag. A preliminary drag analysis has been done for the two configurations with the engine at  $Z_A$  and  $Z_B$  by a thrust-drag bookkeeping process by using the DLR tool *aeroforce*, allowing to separate the propulsion surfaces from the ones contributing to the aerodynamic drag and the evaluation of the correct overall drag. The position  $Z_A$ , i.e. the engine closer to the wing surface, reveals a slightly lower overall drag with respect to the reference configuration, mainly due to the decrease of the wing drag as a possible result of the interaction between engine and wing flow. On the other hand, when the engine moves closer to the wing's surface, the positive contribution in terms of outer nacelle drag is decreasing. In the near future, numerous positions of the engine will be object of this drag analysis together with a drag breakdown into physical components. The aim will be the selection of the configuration with the engine position corresponding to the minimum installation drag at fixed lift coefficient. The pylon will then be integrated in the geometry and a shape optimization process of wing/nacelle/pylon will be conducted to select the optimum reference configuration for high speed. The aerodynamic performance of the selected configuration will then be computed for low speed, to check the angle of attack in landing and the fulfillment of the overall technical requirements.

#### Aeroacoustics

In the low speed configuration the Coanda flap system will be deployed and operate. The main work on assessing the acoustic shielding properties of both the podded and the fully integrated nacelle positions will be investigated. In this first phase of the acoustic shielding study the actual wing is replaced by a simple non-swept wing, depicted in fig.8. The actual airfoil was replaced by a NACA0012 geometry while the local chord length was kept at 4m. Since the fully integrated installation may influence any cut-off properties of the (non circular) intake duct (see left of figure5) the acoustic simulation has to be conducted for the entire arrangement of at least wing and nacelle together. The best shielding properties are expected from the fully integrated arrangement since the solid angle between any source point on the fan disk and the (shielding) wing grows as it approaches the wing surface. Also boundary



Figure 6: Pressure diagrams along the span for three different engine positions and for the WB.

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Figure 7: Influence of the embedded engine installation on the pressure coefficient at different angles of attack

layer refraction effects become more and more beneficial. These positive installation effects are counteracted by the fact that additional sound is generated at the fan due to boundary layer ingestion. The acoustic installation studies have started to estimate the first order effects based on DLR's fast multipole boundary element solver<sup>12</sup> in combination with a simple rotor loading noise model which may include non-uniformity effects. The acoustic simulations mainly serve to quantify uncertainties in shielding prediction when the engine source is assumed as a point source as is the case for preliminary design studies with low fidelity methods (see item 8 below). For this purpose, in a first step the sound radiation of the isolated nacelle is considered, focussing on the extendedness of this source object. rather than the exact prediction of amplitudes. This is accomplished by representing the aeroloads of the  $n_B$  fan blades by the respective number of rotating point forces placed inside the nacelle including  $n_S$  stator blades. The far field of this rough approximate model of the fan source is computed using the DLR BEM code FM-BEM. In the final phase of the study this far field in turn will be back-propagated to the surface of a small sphere, which mimics a representative directed point source as used in the ray approach for the preliminary design study. The mentioned back propagation itself requires complex regularization.<sup>13</sup> Again using the BEM approach an acoustic shielding simulation is then carried out based on this "point source". The acoustic farfield of the installed source is compared to the result obtained when the complete nacelle is taken into account. In this first preliminary study the point source is assumed to be a monopole or dipole respectively. The case of a turbofan with  $n_B = 23$  rotor blades and  $n_S = 8$  stator blades and a shaft RPM of  $N = 2400 \text{min}^{-1}$  is considered, resulting in a blade passage frequency of BPF = 920Hz. In the remaining text only this frequency is considered in this paper. Also, only the podded engine installation is considered here.

Figure 9 shows the nearfield of the three investigated source representions at the wing. The respective ground contours 120m below the source are found in figure 10 on an area extending 400m along the flight direction and 200m in the spanwise direction while being centered at the position of the source. The left hand row of diagrams depicts the uninstalled pressure levels. For this study the source strengths of the poles were adjusted such that the energetic mean of the pressure field over the area corresponds to the one of the nacelle case. The right hand row in figure 10 corresponds to the related wing installed situation. It is obvious that the pressure fields are vastly different depending on the source representation. However the upstream attenuation of the fields is clearly visible for all three cases.

In order to obtain a better quantitative comparison of these results, the pressure fields were energetically averaged over the spanwise extend of the ground domain. The corresponding averaged levels are depicted in figure 11. Again, the strong shielding attenuation becomes obvious in the domain x < 0m in spite of the different source models. It is most interesting to observe that the actual attenuation



**Figure 8:** Simplified setup for acoustic shielding studies on fan noise. top left: aircraft configuration bottom left and right: simplified setup for acoustic BEM simulations. Red sphere indicates position of monopole or dipole respectively.

 $\Delta$ SPL = SPL(installed) – SPL(isolated) shown on the right of figure 11, is relatively independent of the source. All cases show a maximum attenuation on the order of -12 dB. In particular, the attenuation curve of the monopole source representation compares surprisingly well with the complex nacelle source. The dipole source cannot represent the complex situation as accurate. For instance, due to the zero emission of the source perpendicular to the dipole axis, there occurs a "singularity" near overhead position  $(x \simeq 0m)$ . From the above analysis one may conclude that the estimation of the fan noise shielding properties of an overwing engine configuration as that for the REF3 configuration the use of simple point sources seems quite reasonable. For the arrangement studied a replacement of the complex fan mode pattern exiting the nacelle by a monopole placed on the fan axis and inside the intake plane of the nacelle yields about the same attenuation of the level on the ground. While the local interference pattern show differences in the range of a few decibels the agreement is quite satisfactory on a more global level. One must bear in mind that the conclusion may not hold for more general arrangements, different from the one considered, where the entire shielding object (wing) is located on one side of the source (intake) plane. For an actual prediction of the installed fan noise levels on the ground the use of the point source approximation may be critical since the proper representation of the actual source directly influences the result. The accuracy of a ray tracing approach with a directed point source to compute the installation effect remains to be investigated by comparison with the results of the BEM



**Figure 9:** Pressure level *SPL* on wing for three different fan source representations. Left: source field structure for actual nacelle, center: monopole, right: dipole with axis along flight direction.

approach presented.

#### 2. High lift noise reduction by advanced porous materials (sub project A1)

The choice of a Coanda flap system as the key technology for the high lift system avoids the main source of noise in conventional high lift systems, which is related to the slots between either slat and main element or main element and flap. Also, the track systems, supporting slat and flap are located in the highly turbulent (fast) slot flows and represent significant sources as well. A Coanda system may be a particularly silent device in that sense and acoustic wind tunnel tests showed this potential in the mid to high frequency range;<sup>10</sup> however, trailing edge noise at the flap is potentially increased due to the energized, highly turbulent boundary layers on the flap. One quite efficient way to reduce edge noise is the use of porous / permeable materials in the edge area of the respective aerodynamic component of interest.

Therefore the overall aim of the subproject A1 is to develop a physical understanding of the mechanisms responsible for the generation and reduction of airframe noise at active high-lift systems. First, a simulation method is set up to obtain an insight into the principal functioning of complex - meaning anisotropic as well as non-uniform - porous materials as a means of reduction of turbulent-boundary-layer trailing-edge noise. From there on, a design study is carried out to find the most favourable material properties, which are to be realized in subproject A4 (see item 4 below). Second, the different airframe noise source mechanisms of an active high-lift system with a Coanda flap are to be evaluated by numerical as well as experimental investigations. Finally, the found knowledge about noise generation and reduction shall be combined to derive a quiet design of a Coanda flap with inlays made of porous



Figure 10: Ground level contours for three different fan source representations from fig.9, 120m below source. Left: isolated source, right: respective over wing-installed source.



Figure 11: Spanwise averaged ground levels for three different fan source representations from fig.9, 120m below source. Left/centre: nacelle source vs. monopole/dipole source, dashed= isolated, solid=installed. Right: attenuation (difference of installed to isolated levels).

#### material.

As proposed by Faßmann et al., porous materials are modeled by a volume averaged formulation of the flow variables.<sup>14</sup> By this, a set of volume averaged Linearized Euler Equations (LEE) is derived which take into account non-uniformity of the modeled material. The equations depend on certain characteristic parameters of the porous material, which are namely the porosity  $\phi$ , the permeability  $\kappa$  and the Forchheimer coefficient  $c_F$ . In general the latter two parameters are symmetric  $3 \times 3$  tensors.

$$\kappa = \begin{pmatrix} \kappa_{xx} & \kappa_{xy} & \kappa_{xz} \\ \kappa_{xy} & \kappa_{yy} & \kappa_{yz} \\ \kappa_{xz} & \kappa_{yz} & \kappa_{zz} \end{pmatrix} \text{ and } c_F = \begin{pmatrix} c_{F_{xx}} & c_{F_{xy}} & c_{F_{xz}} \\ c_{F_{xy}} & c_{F_{yy}} & c_{F_{yz}} \\ c_{F_{xz}} & c_{F_{yz}} & c_{F_{zz}} \end{pmatrix}$$

In order to obtain an insight into the sound generation process at a porous trailing edge, two different



Figure 12: Test case for the computation of the effect of a porous trailing edge insert on the noise generation by a single turbulent eddy passing the trailing edge of a NACA0012 airfoil.<sup>19</sup>

types of simulations are run. In a two-step hybrid CFD/CAA procedure the generated noise is simulated with the DLR-PIANO-CAA-Code.<sup>15</sup> First, a time-averaged turbulent flow needs to be computed by a CFD solver. Since the mean flow along with the turbulence is influenced by the porous material the CFD needs to contain a suitable porous flow model as well. During the first funding period of CRC880 DLR's TAU-code was extended with a respective model (sub project B5, see below). Then, in the CAA step, time dependent linear propagation equations are solved to obtain the acoustic field. Thereby, the sound sources need to be posed explicitly. In the first place, a single vortex is convected with the mean flow along the airfoil. This can be used to develop a physical understanding of the sound generation because it focuses on the elementary process of a turbulent eddy passing the trailing edge. Unfortunately, this approach does not provide any data that is directly comparable to the experimental findings by Herr et al.,<sup>16</sup> thus it can not be easily verified. Here, the second type of simulations comes into play, which provides a reconstruction of the turbulent eddies inside of the boundary layer of the airfoil. This source is computed by the Fast Random Particle-Mesh Method (FRPM), a synthetic turbulence method based on the turbulence statistics of the time averaged CFD solution.<sup>17</sup> With this method, the broadband noise spectra can be computed, which are directly comparable to the



**Figure 13:** Sound generation due to passage of eddy past trailing edge of NACA0012 airfoil, solid: black, porous aluminum: red, artificial porous material: blue dashed. Left: time signal of a microphone placed at 90° above tailing edge, right: snapshot of pressure response to vortex passage. CAA simulation with PIANO solving the LEE

experimental investigations.

In the current work, the equations for complex porous materials have successfully been implemented into PIANO. Hereby, a new formulation for all derivatives across the discontinuous interface between the porous material and the surrounding flow had to be set up.<sup>18</sup> With this formulation, successful CAA simulations of a single vortex passing in the boundary layer of a NACA0012 airfoil with chord length c = 0.4m and a porous trailing edge starting at 88.75% chord length have been run (cf. figure 12). In this case the material modeled was (homogeneous, isotropic) porous aluminum with a porosity  $\phi = 0.46$ , a permeability  $\kappa = 1.24 \cdot 10^{-10} \mathrm{m}^2$  and a Forchheimer coefficient of  $c_F = 0.1$ . Figure 13 shows the time signal registered by a microphone at  $90^{\circ}$  above the trailing edge of the airfoil. It can be clearly seen, that the porous trailing edge plays a favorable role with regard to the emitted sound. The maximum of the pressure signal is located at t = 0.004 s, which is when the vortex is passing the edge of the airfoil. With the porous trailing edge a pressure signal reduction of around 3.5 dB is obtained. At a simulation time of t = 0.0025 s the airfoil with the porous trailing edge produces additional noise due to the material inhomogeneity at the beginning of the porous material. To investigate whether the simulations give the same broadband noise reduction as the measurements, figure 14 illustrates the associated third octave band spectra. Note, that for the measurements a different airfoil has been used (DLR-F16 instead of NACA0012). Nevertheless, the influence of the porous trailing edge on the simulated sound spectra is in very good accordance with the experimental findings. However, to continue the investigation of anisotropic as well as non-homogeneous materials simulations with a single vortex have been run. Only here the secondary sound source at the beginning of the porous material becomes directly visible. This is of special interest, as it can be shown that for homogeneous materials exists a natural limit to the potential noise reduction. With highly permeable materials, the source location at the beginning of the porous material will become the dominant one.<sup>19</sup> This is illustrated by the time signal of the artificial porous material in figure 13. Here, the use of non-homogeneous material is expected to be beneficial as a more smooth transition from solid material to the free flow is achieved. A first test of a linearly graded material supports this approach by combining the positive effects of a highly and a less permeable porous material.<sup>19</sup>

Another aspect of the project is the investigation of anisotropic materials. Here, it was found that for the noise reduction the permeability perpendicular to the chord, enabling the communication between



Figure 14: Third octave band spectra from simulations of a NACA0012 airfoil and measurements with a DLR-F16 airfoil equipped with solid and porous trailing edges made from porous aluminum.

the airfoil's upper and lower side, is the main influencing parameter.<sup>19</sup> Contrariwise, the permeability along the chord has only little effect on the emitted sound and is limited to a cone of  $60^{\circ}$  downstream of the airfoil. Since here the sound levels are much smaller, this effect is of less interest for now. In application to Coanda flaps with a downward facing trailing edge this effect is certainly to be considered in the future work.

For the upcoming work, the simulations to investigate the noise generated by a Coanda-flap high-lift system are to be run. Additionally, aeroacoustic wind tunnel tests will be conducted on the same Coanda-actuated (DLR F16) model airfoil as in sub project B5 (see item 3 below). By the end of the project in 2018 a design for a low noise Coanda-flap high-lift system with porous inlays is to be derived and simulated.

#### **3. Aerodynamic assessment of porous materials** (sub project B5)

The passive source noise control by use of permeable materials at the wing and flaps has potential consequences on the aerodynamic performance of the wing at high and low speed. The viablity of the desired a/c therefore critically depends on ensuring appropriate aerodynamic characteristics of the a/c. As described in Herr et al,<sup>20, 21</sup> a significant reduction of noise can be achieved by implementing porous trailing edge on an aircraft wing. At the same time however, the implementation of the porous trailing edges is expected to alter the wing aerodynamics. In this sub project, a volume and Reynolds averaged Navier-Stokes (VRANS) model is developed to model the turbulent flow around a porous surface. A set of equations for computing the flows in the porous media have been developed previously<sup>24, 23</sup> by extending the JHh-v2<sup>29</sup> Reynolds stress turbulence model with volume averaging of the Navier-Stokes equations. The momentum and turbulent transport equations are extended by the Darcys law with Forchheimer correction<sup>28</sup> in order to include the contribution of porous medium. The resulting equations have been integrated into the DLR-TAU flow solver. In the first funding phase of CRC880, the numerical model was restricted to isotropic and uniform porous media. In the current funding phase, it has been extended to further include linearly varying porous properties (porosity, permeability and Forchheimer coefficients).

Initially, the validation cases for the VRANS model were restricted to historic DNS-data<sup>22</sup> of a generic channel flow. Afterwards, wind-tunnel experiments on a 2D airfoil with porous trailing edge were conducted to further validate the numerical model.<sup>25</sup> This numerical model is now being used to study a number of test cases where a porous trailing edge is implemented on the modified DLR F15 airfoil with droop nose and Coanda blowing<sup>30,31</sup> with an aim to identify a porous material with acceptable losses in lift while maintaining promising material properties for noise reduction. A number of configurations with different momentum coefficients  $C_{\mu}$  of the Coanda blowing are being considered at this time to vary the amount of flow separation. As an example, the mean flow fields around the solid and porous trailing edges are shown in Figure 15, for a Reynolds number  $Re = 12 \cdot 10^6$ , blowing momentum coefficient  $C_{\mu} = 0.035$  and angle of attack  $\alpha = 12.25^{\circ}$  which corresponds to  $C_{Lmax}$  for the configuration with solid trailing edge. The porous trailing edge leads to a small reduction in lift by approximately 3 % where the  $C_{Lmax} = 4.41$  compared to  $C_{Lmax} = 4.55$  for the solid trailing edge. This can also be seen in the pressure distributions for the porous trailing edge in Figure 16 where the suction peaks are smaller at the leading edge and at the Coanda curvature compared to the solid trailing edge.



Figure 15: Mean flow field around the droop nose airfoil at  $C_{Lmax}$  configurations for  $Re = 12 \cdot 10^6$ ,  $C_{\mu} = 0.035$ , left: solid trailing edge, right porous trailing edge.,  $\phi = 0$ . &  $\kappa = 1.0 \times 10^{-10}$ .

In addition to the different momentum coefficients  $C_{\mu}$ , a number of configurations for Reynolds number  $Re = 1 \cdot 10^6$  are also being studied. It is intended to experimentally validate the results of the numerical model for the latter in the windtunnel before the end of this second funding phase.

Through collaboration with the subproject C4,<sup>2</sup> an automated method for calibration of modeling parameters has been developed and tested.<sup>26</sup> A total of six modeling parameters are included in the numerical model because of the special conditions that are implemented into the turbulence equations in order to accurately resolve the transition across non-porous - porous interface. These model parameters govern the flow at the interface with the fluid and inside the porous media. This state-of-the-art calibration tool has been tested for the DNS-data<sup>22</sup> of a generic channel flow. The results show a good agreement between the parameters obtained from the calibration tool vs. a manual calibration documented<sup>27</sup> previously. The calibration tool would next be used to obtain model parameters for realistic porous materials such as Porous Aluminum 80-110 and others. Simultaneously, the numerical model will be extended for nonuniform and anisotropic porous materials, which would be tested and validated by the end of 2018.

## 4. Development of aeroacoustically tailored materials (sub project A4)

The key noise reduction concept on the Coanda flap is relying on suitable permeable (porous) materials.

In the sub project A4 porous materials for low-noise trailing edges are structurally and mechanically characterized. First experiments have proven a high noise reduction potential for porous aluminum materials, that are produced using a salt infiltration technique. The porous aluminum is available with various pore sizes and were received from "Exxentis"<sup>a</sup>. Although porous trailing edges of porous aluminum show a significant trailing edge noise reduction for a wide range of frequencies, additional high frequency noise may be generated, due to the rough surface and the edges introduced by the pores of the porous aluminum. To reduce this noise it is a major objective of A4 to optimize the porous structure and adjust porosity and pore shape of the porous aluminum.

To reduce the number of edges perpendicular to the main flow, the porous aluminum was formed in a cold rolling process to elongate the pores with the material flow in the direction of rolling. For the

<sup>&</sup>lt;sup>a</sup>Exxentis Ltd, Schartenfelsstrasse 6, 5430 Wettingen, Switzerland



Figure 16: Mean pressure distribution for the airfoil in Fig. 15 with and without porous trailing edge.

experiments a porous aluminum with relatively large pores and a porosity of about 57% was chosen, allowing an adjustment of pore size and porosity on large scale. For the structural characterization of the porous materials and to analyze the evolution of the porous structure during the rolling process, three dimensional X-ray scans are used. The porosity can directly be determined from the 3D reconstructions, whereas the pore size and pore shape is determined from 2D image stacks, extracted reconstruction parallel to the three main surfaces of the rolled plate (parallel and perpendicular to the rolled surface). To measure the pore size, a line segmentation technique<sup>32</sup> was applied to binarized black and white images, giving a mean segment length of black and white segments (pores and ligaments respectively) for various orientations.

First results show, that an open porosity, essential for low-noise trailing edges, is maintained even for a high degree of deformation. Figure 17 shows a three dimensional reconstruction of the porous aluminum after 50% reduction in thickness. Here the pores, that make up still 29% of the material volume, are shown in red (one interconnected pore volume) and blue (pores that are not connected due to the limited reconstructed volume). The results of the line segmentation technique, that are plotted as structural ellipses in Figure 18, reveal an increasing aspect ratio for the pores with an increasing degree of deformation. In this figure the pores are named after the direction of the pore chanel with respect to the rolled surface and the rolling direction. Consequently pores measured in planes parallel to the rolled surface are called "normal", pores measured in planes perpendicular to the rolled surface and the rolling direction are called "parallel" and pores measured in planes perpendicular to the rolled surface and parallel to the rolled direction are called "transverse". The pore size in rolling direction is always plotted horizontally and indicated by an arrow, while the pore size in the direction of compression in the rolling gap is always plotted vertically. While the pores have about the same size in every direction before rolling, the pore structure becomes anisotropic during rolling. Because the porous aluminum is compressed in the rolling gap, the pore size perpendicular to the rolled surface after rolling is smallest. Due to an elongation of the pores with the material flow, the biggest pore size can be found in the direction of rolling. Consequently transverse pores have the biggest aspect ratio. The aspect ratio, determined from the mean pore size in the direction of rolling and the mean pore size perpendicular to the rolled surface, increases up to about 1.5 for the rolled condition with 50%reduction in thickness. Flow resistivity measurements in sub project A6, that are discussed in detail



**Figure 17:** Reconstruction of the porous aluminum PA 200-250 after a reduction in thickness of 50%. (a) Reconstruction of the material surface, (b) reduction of the pore volume.

elsewhere,<sup>32</sup> reveal the expected increasing flow resistivity with an increasing degree of deformation from about  $45 \cdot 10^3 Ns/m^4$  up to  $123 \cdot 10^3 Ns/m^4$  for the direction perpendicular to the rolled surface.

The influence of the rolling process on mechanical parameters of the porous aluminium is investigated using tensile tests. Test samples of the as received and rolled porous aluminum are oriented parallel and perpendicular to the rolling direction, to detect anisotropic mechanical behavior. First results show that the mechanical parameters are not reduced by the material deformation during the rolling process. Also the isotropic mechanical behavior of the as reveived porous aluminum is maintained up to 50% reduction in thickness. In fact the mechanical parameters that were calculated for the sample cross section, without taking the decreasing porosity into acount, are increasing with the degree of deformation. Mechanical parameters that are calculated with the porosity as a correction factor remain roughly constant. Thus the mechanical parameters are dominated by the load-bearing cross-section, whose proportion is increasing with the degree of deformation. A notch effect of the pores or critical



Figure 18: Structural ellipses of the as received and rolled porous aluminum PA 200-250 with selected degrees of deformation. (a) Pores normal to the rolled surface, (b) pores parallel and transverse to the rolling direction.

damage during the rolling process is not observed.

In total the structural and mechanical results prove the porous aluminum to be a well suited material for porosity adjustments in a cold rolling process. To further increase the aspect ratio during the cold rolling process a tensile loading will be added to rolling experiments. Secondly a continuous transition from solid to porous material shall be created to minimize the acoustic effect at the leding edge of the porous trailing edge insert (see item 2 above), using a special rolling mill, that allows to adjust the rolling gap during rolling.

#### 5. Pore resolving LES simulation of porous materials (sub project A5)

The aerodynamic and even more so the acoustic characteristics of porous materials is not well known, particularly when installed below a turbulent boundary layer. Moreover, the physical mechanisms behind the effect of porous materials on flow and acoustics are not understood. The aeroacoustics of these materials is particularly interesting, since in the intended application these do not act as classical absorbers; they rather influence the turbulence related source of sound by affecting the near field. In order to investigate this extremely complex flow physics a lattice Boltzmann approach is employed which enables the resolution of all individual pores of an actual material.

A major goal of subproject A5 is to investigate the aeroacoustic effect of permeable materials in laminar and turbulent flow by pore-scale simulations using DNS and LES methods within and in the boundary layer of porous materials. A large number of time-dependent simulations are carried out in highly complex three-dimensional pore scale resolving tomography-based flow geometries to obtain turbulent flow statistics which are used to calibrate the homogenized (V)RANS models in subproject B5.

The permeability and Forchheimer coefficient are important modeling parameters in (V)RANS and volume averaged CAA methods investigating aerodynamic/acoustic characteristics of airfoils with porous inlays. These parameters are computed on the resolved pore scale LES/DNS based by the cumulant LBM<sup>33</sup> which is a parameter-free DNS-LES model for incompressible and weakly compressible aero



Figure 19: Normalized permeability of porous aluminum PA80-110 for different Reynolds numbers.

Material	$\kappa \times 10^{-10}, m^2$	$C_F$	$r_{LBM}, Ns/m^4$	$r_{exp}, Ns/m^4$	deviation, $\%$
PA80-110	1.28675	5.0583	142279	145490	2.2
SBP120	2.80362	0.6581	65058	64686	-0.6

Table 1: Results of the simulation for porous aluminum PA80-110 and sintered bronze SBP120.

acoustical flows. The simulations use highly resolved ( $\sim 3 \times 10^9$  voxels) CT scans of porous materials. A pressure gradient is applied in flow direction and no-slip boundary conditions are applied in normal and spanwise direction. The simulations are conducted for different Reynolds numbers. Figure 19 shows normalized effective permeability as a function of Reynolds number for porous aluminum PA80-110 that was computed in conformity with the Darcy law.<sup>34</sup>

$$-\frac{dp}{dx} = \frac{\mu}{\kappa} u_D,\tag{1}$$

where  $\frac{dp}{dx}$  is pressure gradient and  $\mu$  is dynamic viscosity and  $\kappa$  is permeability. The Darcy velocity  $u_D$  is computed as the product of the averaged pore velocity  $\langle \bar{u} \rangle$  and the porosity or as the ratio of the flow rate Q and the cross section area A of the porous medium:

$$u_D = \langle \bar{u}_p \rangle \phi = \frac{Q}{A}.$$
 (2)

The Forchheimer coefficient is computed by applying Forchheimers equation to this data

$$-\frac{dp}{dx} = \frac{\mu u_D}{\kappa} + \frac{c_F}{\sqrt{\kappa}} \rho u_D^2.$$
(3)

Table 1 shows the computed permeability ( $\kappa$ ), Forchheimer coefficient ( $C_F$ ), length related flow resistance ( $r_{LBM}$ ) and deviation from the experimentally determined flow resistance ( $r_{exp}$ ). The porous materials studied so far are isotropic. Ongoing computations will address the full permeability tensor of anisotropic porous materials.

Additional modeling parameters for (V)RANS methods are determined by pore scale simulations of turbulent channel flow with a porous wall. The resulting turbulence statistics as well as the detailed



Figure 20: Simulation setup of turbulent channel flow with permeable wall.



Figure 21: Mean velocity profile above and inside porous medium in a channel flow.

profile at the porous interface are used for improved turbulence simulations on a homogeneous scale for porous aluminum. Figure 20 shows the simulation setup. The length of the computational domain is 64 mm, the height is 17 mm and the depth is 8 mm. Periodic boundary conditions are used in streamwise and spanwise directions. No-slip boundary conditions are used in wall-normal directions. Adaptive forcing based on a proportional-integral-derivative (PID) controller is applied in order to achieve the bulk Reynolds number Re=51000. The porous bed is constructed with 32 mirror voxel sets of the porous aluminum PA80-110 scan, each of which has dimensions of  $4 mm \times 4 mm \times 1 mm$ . The computational grid consist of  $1.2 \times 10^9$  nodes. The resolution of the grid close to the top and bottom walls and inside the porous aluminum is  $10\mu m$  corresponding to the normalized wall distance on the top of  $z^+ \simeq 1$ . The simulation reaches the dynamic steady state after 50 eddy turnover time (ETOT). Additional 10 ETOT are used for collecting the turbulence statistics. The simulation was performed on the Cray XC40 at North-German Supercomputing Alliance (HLRN) and used about 2 million core hours. Figure 21 shows the normalized mean velocity profile of the channel flow. The left picture shows a zoom of the mean velocity inside porous media. The negative velocity in the upper part of the porous aluminum is due to the small recirculating flow. This effect is not captured in the current volume averaged RANS model.

Presently computational setups are prepared for pore scale simulations around a DLR-F16 airfoil to investigate the aeroacoustic effect of permeable materials in turbulent flow with a target Reynolds number of  $10^6$  related to chord length with a minimum resolution of about 20  $\mu m$  and a grid consisting of app.  $3 \times 10^9$  points.

#### 6. Volume averaged LES of porous materials (sub project A8)

In view of the boundary condition of a very fast (high subsonic) Coanda jet flow control, compressibility effects may not be neglected at the actual Coanda high lift system considered. For this purpose a continuum mechanical approach, based on the Navier-Stokes equation for compressible flows is mandatory. In this case the overall computational effort is so large that in this approach the porosity of the material is modelled via volume averaging.

Although it has long been known that the application of porous materials at edges leads to a sound reduction, the reason for this reduction remains unclear. The project aims to further enhance the understanding of the source mechanisms of solid and porous materials inside turbulent flows by the use of scale-resolving simulations. On the basis of Overset Large-Eddy Simulations (OLES), the source mechanism and sound reduction of porous materials are investigated in the second funding phase of the Collaborative Research Centre CRC880. To reduce the computational effort, the porous material will be modelled with a volume-averaged approach.

The basis of the present work are the viscous Non-Linear Perturbation Equations (NLPE), which are derived from the compressible Navier-Stokes equations in non conservative form. The primitive variables are decomposed into a base flow part and a fluctuating part, e.g., by substituting the  $p^0$  and p'. Terms containing solely background flow contributions are grouped on the right-hand side. Typically, these source terms represent the residual turbulent viscous stress and heat flux, whose definition is related to the choice of the base flow. In general, the only assumption made is that the background flow is also a solution of the Navier-Stokes equations. For a detailed derivation, the reader is referred to Refs.<sup>36, 37</sup> The such obtained hybrid approach<sup>38</sup> is called "Overset", similar to the one proposed by Terracol.<sup>39</sup>

The CAA-Code PIANO<sup>40</sup> is a structured code, based on curvilinear, multi-block grids. In addition to the above mentioned viscous NLPE, it also supports the computation of sound propagation by the Linearized Euler Equations (LEE), Acoustic Perturbation Equations (APE) and non-linear Euler equations in primitive disturbance form as governing equations. Spatial gradients are approximated by the Dispersion Relation Preserving (DRP) scheme,<sup>41</sup> whereas temporal integration is facilitated by a 4th-order low-dispersion Runge-Kutta (LDDRK) algorithm.<sup>42</sup>

Isotropic decaying turbulence is a canonical test case for higher-order CFD methods. Furthermore, it serves the purpose of a generic test case for the subgrid-scale investigation. The flow is initialised with highly resolved DNS data from Wray<sup>43</sup> after which decay sets in. The calibration simulations were performed at  $Re_{\lambda} = 104.5$  on a  $64 \times 64 \times 64$  grid. By varying the Smagorinsky constant  $C_S$  and comparing the results with the corresponding filtered DNS reference spectra, the scaling and temporal decay can be evaluated. This procedure is illustrated in Fig. 22 (left) for only three small variations of the Smagorinsky constant. For the case of no sub-grid scale model a significant energy pile-up towards the cut-off wave number  $\kappa_c$  is observed (not shown). By enabling the subgrid-scale functionality, the spectrum can be tuned towards the DNS reference. Whereas  $C_S = 0.135$  is too less dissipative and  $C_S = 0.155$  seems to overemphasize the eddy viscosity contribution,  $C_S = 0.145$  can provide for the appropriate amount of modeled dissipation.<sup>44,46</sup>

The Overset method is beneficial, as it is applicable in a restricted regime where sound sources are active, e.g., a turbulent boundary layer convecting over a trailing edge. In the particular example of trailing-edge-noise, the question arises how to provide for a proper turbulent inflow. This is facilitated by stochastic turbulence forcing with FRPM.<sup>48</sup> Based on the turbulence statistics of the underlying RANS mean flow, velocity fluctuations are reproduced, which are subsequently injected into the viscous



Figure 22: (left) 3D Energy spectrum for various Smagorinsky constants at time t = 1/3, 3 and 5. DNS is indicated by symbols and viscous-PIANO with solid lines. (right) Snapshot from Overset LES simulation of NACA0012 at zero angle of attack (grayscales: instantaneous pressure fluctuations p' and iso-surfaces: turbulent structures visualized with the Q-criterion where colours represent local Mach number).

PIANO simulation with the eddy-relaxation term.<sup>47,46</sup> In Fig. 22 (right) a snapshot of the Q-criterion is depicted showing the Overset LES simulation approach of the NACA0012 trailing-edge. At the time being isotropic Gaussian turbulence is reproduced, nevertheless one can see that initially isotropic structures inside the FRPM forcing region become anisotropic while being convected towards the trailing edge. It is noteworthy to mention that the establishment of the turbulent field, necessarily accompanied by the mentioned transition into anisotropy takes place right downstream of the FRPM box (see insert in Fig 22). This behaviour shows that the realization of turbulence inside the FRPM box is quite close to its real behaviour. Otherwise a marked transition zone would appear downstream of the patch. Moreover, the depicted pressure signal clearly shows the expected antiphase cardiodic pattern, which can only emanate from the edge as a result of the physical trailing edge noise mechanism. Artifical sound signals, potentially arising from less advanced stochastic turbulence models are not observed. A more detailed description can be found in Ref.<sup>45</sup>

#### 7. Cabin noise excitation of UHBR jet engines (sub project A6)

While the use of UHBR or even extremely high bypass ratio engines reduces the jet noise levels substationally at low and high speed conditions, the question arises, what consequences may be expected for the cabin noise excitation in cruise flight. In a comparison between the considered a/c concept with conventional under-the-wing nacelles an influence may be expected due to the different engine positions. However, a much more important effect is expected according to the fact that the maximum in the UHBR engine's spectrum is shifted to substantially lower frequencies since the jet flow speed is reduced and the dimensions are increased. Therefore the question arises, whether the (at first sight positive) noise reduction really translates to the cabin interior. This is a non-trivial question because the transmission of low frequency sound through the fuselage structure may be much less insulated compared to higher frequencies of a conventional engine.

The main goal in work package A6 is to investigate the influence of an ultra high bypass ratio (UHBR) engine on the cabin noise of the reference aircraft. To assess the noise level, a comparison of the impact of jet noise on a generic fuselage between a conventional engine (BPR 5) and the UHBR engine is conducted. Furthermore, passive structural measures at the joints of the secondary structure (cabin panels) are studied to reduce the sound transmission through the fuselage. To assess both engines regarding the resulting cabin noise, the yield surface pressure fluctuations are weakly coupled into a mechanical model of the fuselage primary structure. Both, the structure-borne and airborne sound path into the cabin are considered within the fuselage model with which possible damping and damming measures at structural parts are investigated.

Computational Aeroacoustic (CAA) computations are carried out by means of the DLR CAA solver PIANO combined with the FRPM method<sup>48,49</sup> to model 3D stochastic sound sources. To capture the fine scale jet noise, the Tam & Auriault<sup>50</sup> model is involved. The 3D full scale simulations cover the area which is directly affected by the jet up to the fuselage surface, where the refraction effect of the turbulent boundary layer is taken into account. The mechanical model of the fuselage is discretised



Figure 23: Preliminary results for the instantaneous surface pressure fluctuations for the UHBR (left) and conventional BPR5 engine (right).



Figure 24: Structural model of the considered part of the fuselage.

by use of the Finite Element Method (FEM) for the structural and fluid domains in the interioir and weakly coupled to the exterior pressure loads by the CAA computations.<sup>52, 53</sup> The work group's inhouse code ELPASO is applied as FE implementation. The final result will be the sound pressure level at the passenger's ear position.

To verify the 3D results, CAA computations for the isolated jet with the well established PIANO/RPM modal approach<sup>56,57</sup> have been conducted. Fig.23 shows the preliminary results for the surface pressure fluctuations on the fuselage. Qualitatively the absolute pressure levels for the UBHR engine are, as expected, lower. Furthermore the affected position on the fuselage and accordingly the influence of the boundary layer refraction is different due to different incidence angles.

The comparison of the preliminary 3D results and the findings of the computations for the isolated jet shows up discrepancies between the maximum of the related jet noise spectra. The 3D results appear to be shifted to higher frequencies. This point is also noticeable by the small size of the structures on the surface, which are for the UHBR in the same range or even smaller than for the conventional engine. This issue is associated with the fact, that two-point space-time cross-correlation functions realized by the FRPM model slightly differ from the functions implemented in the original Tam & Auriault model. The discussion of this issue and ways how to tackle it, will be shown in Neifeld & Ewert.<sup>58</sup>

On the basis of a preliminary structural aircraft design given by PrADO,<sup>60</sup> a generic model of the fuselage is derived. The main assumptions are a stationary response in cruise flight, a symmetric problem and a neglected influence of the aircraft's structural front partition. The structural part, depicted in Fig.24, considers the primary structure (outer shell, frames, floor, bulk head) and the secondary structure (cabin linings). The fluid part consists of the insulation (typical glass wool) and the cabin fluid (air). Both parts are strongly coupled<sup>51,55</sup> and solved in frequency domain by means of the finite element method (FEM). Fig.25 shows the two parts of the mechanical model including the mesh which is applicable up to 710 Hz. Furthermore, first results on the sum pressure level distribution within the cabin on the passenger ear's height are shown in Fig.25. Due to the assumption of symmetry,



**Figure 25:** Spatial distribution of the  $L_{\sum}$  of the UHBR engine configuration<sup>54</sup> and finite element mesh for solving the fluid-structural model of the aircraft's fuselage.



Figure 26: Double wall test stand (a) and transfer function in front of the secondary aluminium structure with and without elastic joint (b)

only uneven fluid modes are excited which results in a maximum sound pressure level at y = 0 m. As expected, a maximum sound pressure levels also occurs within the edges and on the secondary structure in the back of the aircraft. The chain starting from the preliminary design of aircraft and the prediction of jet noise excitation to the prediction of cabin noise is established this way<sup>54</sup> and can be applied and investigated in further studies. Another important focus within the project is the detailed investigation of crucial structural parts in sound transmission.

The joints of the panels within the cabin are expected to be a crucial path of sound transmission. Therefore, experimental and numerical investigations of idealised fixed and elastic joints have been carried out. The different joint types are integrated into a simplified double-wall test stand which is shown by Fig. 26 on the left. Two rectangular aluminium plates are connected by a stiffener structure at which the different joint types are applied at the four edges of the secondary structure (smaller plate). The primary structure (larger plate) is excited by a electrodynamic shaker and the frequencydependent velocity distribution is measured at the secondary structure. By use of the Rayleigh integral, the transfer function  $T_{pF}$  between the excitation force and the resulting SPL in front of the secondary structure is calculated (centred point at distance  $0.5 \,\mathrm{m}$ ). Fig. 26 shows the change of the frequency response function  $T_{pF}$  due to the introduction of elastic joints. In low frequency ranges between 50 - 200 Hz, a sound reduction of around 10 dB can be observed within the eigenfrequencies of the test stand structure. Above 200 Hz, larger reduction up to 30 dB are reached by the introduction of shock mounts. Of particular interest are the material parameters of the elastic joints which can be determined by use of model parameter updating techniques and correlation criteria as objective function.<sup>59</sup> A simple modelling approach for the joint using visco-elastic beam elements and a volume approach for the aluminium profile has been validated using the experimental results of the test stand and can be included into a full mechanical model of the fuselage. This approach will allow the assessment of sound reduction measures at the secondary structure's joints with respect to the mentioned engine configurations.

The next steps are to finalize the computations for the conventional engine and adapt the setting for the UHBR engine. That implies a shorter CAA domain, though the engine is mounted in the rear position of the aircraft. On the other hand, the time duration of the simulation has to be enlarged, since lower frequency content is expected. On the basis of finalised loads, the generic mechanical model is applied to assess the two engine configurations. To find reasonable measures to lower the sound transmission through joints, the validated mechanical models of the secondary structure's joints are investigated using parameter variation techniques.

#### 8. System noise assessment of complete aircraft (sub project Z)

The objective of the acoustic work package of TP Z is to perform the system noise assessment within the CRC880 to enable a final evaluation of each aircraft. The DLR parametric noise prediction tool PANAM<sup>61</sup> is used to perform the system noise assessment. PANAM uses semi-empirical models for the relevant aircraft noise sources. The shielding effects of the engine fan noise are considered using the DLR ray-tracing tool SHADOW.<sup>62</sup> All input required for noise prediction is available through the conceptual aircraft design tool PrADO<sup>66</sup> of Technical University Braunschweig, Germany. As the CRC880 focuses on new or unconventional technologies, new noise source models have to be integrated into PANAM. These noise sources are ultra-high bypass ratio (UHBR) engine noise, propeller noise, and Coanda flap noise, which are briefly described in the following. This is followed by a short system noise assessment for approach of the REF3. Furthermore, an initial process is described to evaluate the uncertainties of CRC aircraft configurations in the third funding period.

## UHBR

Engine noise in PANAM is predicted using semi-empirical noise source models for jet and fan, respectively. Stone's model<sup>63</sup> is used to predict the jet noise originating from the core and bypass jet. Fan broadband, discrete-tone, and combination-tone noise are predicted with Heidmann's model<sup>64</sup> but with a modified underlying data base. Further details are given in Ref.<sup>61</sup> The underlying data base of Heidmann's model was further modified to allow the prediction of UHBR fans. Figure 27 shows an exemplary comparison of the sound pressure levels between a conventional engine with a bypass ratio of 5 (solid lines) and an UHBR engine with a bypass ratio of 17 (dashed lines). The left figure shows the polar emission directivity at 1 m distance and the right figure shows an emission spectrum at an emission angle of  $134^{\circ}$ . The comparison shows that a noise reduction close to the source in the range of about 8 dB is possible for this specific flight condition. The noise reduction as perceived on the ground, however, can be different due to acoustic installation, moving source effects, atmospheric dampening, ground reflexion, and human perception, all of which can be accounted for within the system noise assessment.



**Figure 27:** Comparison of the noise emission at 1 m between an UHBR-17 and conventional BPR-5 engine (altitude=3000 ft, Mach=0.3, thrust per engine=20 kN)

## Propeller

A simple analytical propeller model from Hanson as described in  $\text{Ref.}^{65}$  is used for propeller noise prediction because also a propeller driven a/c is being analyzed in CRC880. For each flight condition, the model requires the generated thrust, the engine's power, the rotational speed, and the forward flight speed. Although the model is simple, it is able to represent the relevant propeller characteristics. Detailed acoustic installation effects cannot be accounted for what has to be kept in mind when analyzing the results.

## Coanda flap

A Coanda flap noise model suitable for parametric noise prediction is not yet available in the literature. The development of such a model is pursued within the CRC880 for the next funding period. Until then, an assumption for this noise source has to be made. As described in Ref.<sup>67</sup> a Fowler flap model is used as an initial guess. This is a rough estimation but is based on findings in the literature.<sup>68, 69, 70, 71, 10</sup> The initial noise assessment of the REF3 aircraft in Ref.<sup>67</sup> indicates that for a continuous descent approach

the high-lift system may not be the dominant noise source. The Coanda flap causes significant drag which results in an increased thrust and engine noise level. As a consequence, individual technology related low-noise flight trajectories must be developed to minimize the noise on the ground. It is pursued to check the quality of the Coanda flap noise estimation by comparing it with high-fidelity computations of sub project A1 (see above).

#### System noise assessment

Approach and departure trajectories are required to perform the system noise assessment and evaluation of the CRC880 aircraft. The trajectories must be directly available within the conceptual aircraft design phase to consider any change in flight performance. The development of such a tool is ongoing. Within this tool, the aircraft is simplified as a simple mass point. An exemplary vertical approach flightpath with a steep final approach segment down to 1000 ft is depicted for a conventional reference aircraft (KON1) and the REF3 in Fig. 28.



Figure 28: Vertical flightpaths with a steep segment of conventional aircraft (KON1) and the CRC-aircraft with circulation control (REF3)

The engines of both aircraft are set to idle shortly before the top of descent and then descent with 2.0°. At 3000 ft, the aircraft fully deflect their high-lift system and descent with a very steep angle of  $-6^{\circ}$  (KON1) and  $-7.5^{\circ}$  (REF3) respectively. At 1500 ft the landing gear is deployed and at 1000 ft both aircraft are stabilized on a 3° glidepath, i.e. the airspeed has to be kept constant and the thrust is increased accordingly. These flighpaths, together with the aircraft geometry and engine data provided by PrADO, are used to evaluate the noise on the ground. The  $L_{A,max}$  noise contour of the KON1 is shown in the upper part of Fig. 29, whereas the lower part shows the  $L_{A,max}$  noise contour of the REF3.



Figure 29: Comparison of the maximum A-weighted noise level on the ground between a conventional aircraft (KON1, upper part) and the CRC-aircraft with circulation control (REF3, lower part)

For both aircraft, the engine noise dominates the noise on the ground. As the KON1 uses an engine with a bypass ratio of 5 and the REF3 uses an ultra-high bypass ratio engine with a bypass of 17, the noise of the REF3 is significantly lower than the noise of the KON1. Not shown here, but noteworthy, is that the estimated Coanda flap noise of the REF3 is about 7 dB quieter than the engine noise, i.e. it is not contributing to the overall noise significantly.

However, experience has shown that the engine noise calculated based on PrADO engine data is likely to be overestimated. For both aircraft, it is expected that the engine noise can be reduced if the engines are individually designed. In this case, the estimation of the Coanda flap noise is not sufficient anymore, because the importance of the Coanda flap noise increases as engine noise decreases.

System noise uncertainty assessment

System noise assessment of complete aircraft is realized with parametric noise tools as described above. Any evaluation and selection of promising concepts and technologies is based on prediction results by these tools. Therefore, it is essential to identify uncertainties associated with the underlying prediction process. Only if these uncertainties are accounted for, a comparative analysis of prediction results becomes feasible. NASA has established an in-house uncertainty analysis process for their noise prediction tools in 2016.<sup>72</sup> Based on this work and other research activities<sup>73</sup> in the context of aircraft noise, DLR has initiated their own uncertainty assessment for conventional transport aircraft.<sup>74</sup> Three sources of uncertainty are accounted for, i.e. the input data uncertainty, the noise modelling uncertainty, and the propagation uncertainty. A dedicated uncertainty module has been implemented into PANAM to yield a standard deviation for each predicted noise level. Initial application is promising and both temporal and spatial distribution of uncertainty can be identified. This initial process will furthermore be advanced to ultimately yield reliable uncertainties for the technologies and configurations as selected for the CRC880.

## IV. Conclusions

The area acoustics as part of the Cooperate Research Center CRC880, located at TU Braunschweig, Germany considers enablers for low noise aircraft operating with very short field length. A reference configuration REF3 has been designed for this purpose. The research follows two paths simultaneously, i) low noise through aircraft configuration, particulary by engine fan noise shielding and ii) reduction technology for airframe noise based on porous materials. Aeroacoustic simulations are used to specify necessary properties of these materials, indicating clear benefits of graded properties. The materials are produced and characterized. The flow physics of the materials is studied in detail with pore-resolving simulations and experiments; scale resolving simulations are carried out to describe the complex flow near and inside the porous materials. The implications of the low noise short take-off and landing aircraft configuration on the aerodynamic performance and cabin noise are investigated too. In an integration step the configurational and technological findings will be assessed in view of performance and noise.

- CRC880 is an ongoing research initiative into low noise STOL transport aircraft for short to medium range missions
- In order to achieve significant noise reduction for aircraft noise reduction technologies have to be combined with low noise aircraft configurations
- preliminary studies suggest that the full potential for the system noise reduction of the considered aircraft can only be realized in combination with specially adopted flight procedures.

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