“Aircraft Noise Reduction Technologies and Related Environmental Impact”

ARTEM

Project Overview and

Final Achievements at Month 54

Published 30.09.2022

1. General information and project objectives

“ARTEM” – stands for **A**ircraft noise **R**eduction **T**echnologies and related **E**nvironmental i**M**pact.

ARTEM was planned as a four-year research project, started in December 2017, and was devoted to the development of novel noise reduction technologies for low-noise 2035 and 2050 aircraft configurations. Due to the severe impact of the COVID pandemic on experimental activities and other work, a six month no-cost-involved extension was requested and granted. The project ended successfully achieving all of its main objectives in May 2022.

The project was set up in order to help closing the gap between noise reductions obtained by current technologies - as already applied or being matured in large EC technology projects such as OpenAir and CleanSky - and the long-term goals of ACARE. Meeting the ACARE goals of noise reduction of 65% for each aircraft operation in year 2050 compared to the reference year 2000 requires continuous innovation by taking up and investigating promising novel ideas for noise reduction and associated methods for prediction.

In particular, ARTEM explored innovative ideas and concepts for efficient noise reduction by novel liner concepts and investigated the potential of dissipative surfaces as encountered with the development of meta-materials. The aim was to develop those “Generation 3” noise reduction technologies (NRTs) to a technology readiness level (TRL) of 3 (experimental proof of concept) to 4 (technology validated in lab).

Within the project it was considered, that future aircraft, anticipated to be introduced between 2035 and 2050, might have different configurations than the current tube-and-wing design with underwing–mounting of the engines. For 2035, the tube-and-wing layout might persist while the engine placement could differ, e.g. being semi-buried in the fuselage. For the 2050 time frame, blended wing-body aircraft with very high bypass ratio (BPR≥16) may power long-range aircraft, while regional aircraft might exhibit hybrid propulsion systems or distributed electric propulsion systems.

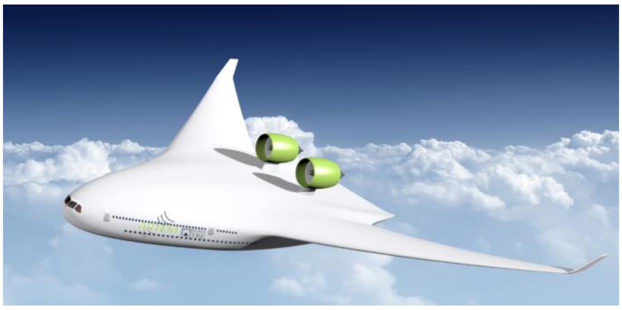


Figure 1: Left: ***A possible candidate for 2035 air transport: ONERAs NOVA concept with semi-buried engine (© ONERA, 2015). Right: Initial layout of a blended wing body anticipated for 2050 operation, equipped with generic UHBR engines mounted on pylons on the top of the centerbody (© University RomaTre, 2018).***

The noise signature of the anticipated configurations will be strongly influenced by the shielding of the propulsion system noise – depending on the type and the actual location of the propulsion system and the interaction of several aircraft components.

The interactions effect of the propulsion system with the high-lift-system and the airframe, inflow distortions for the propulsion system, and the interaction of the landing gear with the airframe are significant noise source already for current aircraft configurations, but will gain even more importance for future highly integrated configurations.

These effects – which directly involve the noise generation - were investigated in the ARTEM framework by dedicated experiments and high-fidelity numerical calculations qualifying and improving prediction methods and investigating potential means of noise reduction.

Reduce noise sources, reduce noise propagation, predict the impact of new aircraft and their noise reduction

The noise reduction technologies were coupled to several configurations derived in a robust multi-dimensional design optimization (MDO) process. Possible future aircraft configurations as the blended wing body (BWB) and other innovative concepts with integrated engines and distributed electrical propulsion were used to predict the anticipated noise and possible noise reductions. The impact of those new configurations with low noise technology was assessed in several ways including industry tools, airport scenario predictions, and auralizations.

Initiated by the Association of European Research Establishments in Aeronautics (EREA), ARTEM followed a holistic approach for noise reduction of future aircraft and provides enablers for quiet air traffic of the future - which is an important part of EREAs Future Sky initiative.

ARTEM brought together the expertise of a large and diverse consortium consisting of twenty-four partners* throughout Europe: national research centers for aviation research, universities, small-and medium-sized enterprises (SMEs), and some of the major European aircraft industry companies.

Project Details

Project ID/Grant Agreement:	769350
Funded under:	Smart, Green and Integrated Transport
Start date:	2017-12-01,
End date:	2022-05-31
Total cost:	7.9 M€
EU contribution:	7.5 M€
Coordinated by:	DLR
Call Topic(s):	MG-1-2-2017 “Reducing aviation noise”
Funding scheme:	RIA – Research and Innovation action
Website:	www.dlr.de/ARTEM

** Due to the Russian aggression against Ukraine starting in February 2022, unfortunately, also the scientific cooperation within ARTEM with the Russian partner TSAGI had to be stopped in the final stage of project.*

2. Executive Summary of Achievements

ARTEM has successfully explored a large variety of concepts for passive and active noise reduction. Two liner concepts, namely the multi-focal and the slanted septum liner concept proved exceptionally good progress with respect to modelling and design methods and expected benefit for application on UHBR propulsion systems for near-term and long-term aircraft configurations. An expected benefit of 0.7-0.9 EPNdB on aircraft level was estimated for a 2025 large long-range aircraft during the industrial assessment. All other concepts have also made significant progress in maturation reaching the expected TRLs of 3-4 depending on starting point. A large number of open publications describe these advancements.

Shielding modelling has been improved and finally successfully applied demonstrating the tremendous benefit with respect to noise reductions for ground observers if propulsion systems are placed on top of an aircraft structure – in particular here for blended wing body aircraft.

The complex flow and noise generation phenomena associated with conventional high-lift systems have been successfully modelled and noise reduction demonstrated by design variation like the very long chord slat (VLCS). The variety of modelling and prediction approaches from quick 2-D tools capable to handle many design variations during an optimization process to high-fidelity simulations including (Overset-)LES for in-depth analysis of noise generation mechanism will prove very useful for future aircraft system development work. Other means for noise reductions (serrations, finlets, porous inserts, etc) have been investigated numerically, experimentally and proved good results on component level, but lower impact during assessment on full aircraft scale.

The boundary layer ingestion concept (BLI), which is anticipated to reduce fuel consumption for “tube&wing” aircraft significantly, has been addressed in a comprehensive way ranging from low-fidelity modelling to extensive numerical simulations on full aircraft scale. The initial focus was on the ONERA NOVA platform, but included finally also the improved NAUTILUS platform. It was coherently demonstrated, that the inflow distortions associated with this concept are prone to increase the radiated propulsion noise – mainly fan noise – significantly. Great care is needed in the design of the inlet duct system to reduce inflow distortion as much as possible with extensive application of liners having the capability to further reduce or avoid any noise penalties. The comprehensive noise assessment and associated publications received great attention in the community.

For aircraft landing systems, a large campaign involved experimental and numerical work on detailed source analysis and promising reduction means as meshes, screens, fairing design, and porous inserts. While already demonstrating some potential noise reduction on model scale and during full aircraft assessment, the work performed in ARTEM constitutes a profound basis for on-going H2020 project INVENTOR work.

As a basis for distributed electric propulsion systems, a detailed study of mutual interaction effects of closely spaced rotors, and between rotor and wing structure has been performed in ARTEM. A purpose-build highly modular test setup consisting of a wing section and 3 propellers mountable in pusher and tractor configuration was used to build-up a huge experimental data base and subsequent data processing and prediction tool chains were developed and validated.

For the early design phase aircraft development, a robust multi-dimensional design optimization tool (MDO) was advanced and subsequently applied to design two blended-wing body (BWB) aircraft configurations:

BOLT: a long-range BWB with optimized low-noise technology and modern UHBR engines placed on top of the fuselage and
REBEL: a short-range BWB aircraft with either classical UHBR engines placed on top of the fuselage and (REBEL-C) or a distributed hybrid electrical propulsion system (REBEL-HEP).
These configurations have been used also in parallel-running H2020 project ANIMA for fleet assessment and will be used in subsequent projects building the basis for more detailed design optimization.

For BOLT, REBEL, but also NOVA concepts a detailed noise assessment, single aircraft noise prediction, and a (limited) final fleet assessment have been made - demonstrating a potential for significant reduction of noise footprint on airports.
The assessment for promising technologies on CleanSky2-derived platforms for short-/medium range (SMR) and long-range (LR) aircraft has been performed by Airbus while a specific business jet platform was used by Dassault Aviation for the same task.

Based on noise predictions of the novel aircraft configurations, auralizations have been generated and used for comparative listening test including also psycho-acoustic aspects of annoyance of future aircraft noise. While currently involving still large uncertainties with respect to specific source characteristics, the work demonstrated successfully the general process of predictions also for novel configurations with detailed validation options of course only for currently existing aircraft.

Benchmark exercises for high-lift device noise prediction, for shielding efficiency, and for noise source predictions and propagation predictions are a further output of ARTEM and have been or will be published soon and thereby support the coherence of approaches of partners in aircraft noise prediction in Europe and around the world.

Building on a close exchange and cooperation between ARTEM and parallel-running H2020 project ANIMA, a chapter on future aircraft design and associated noise implications has been contributed to the open access book “Aviation Noise Impact Management” (Springer, 2022), which has exceeded the total of 25’000 downloads already after 6 months.

ARTEM results and achievements will form the basis for a large number of future higher TRL research activities on national and international level, as for instance the Horizon Europe program of the EC or Clean Aviation activities.

About half of the project duration was impacted with several restrictions due to the COVID pandemic. This applied in first place in a very severe way to experimental activities, but also to all other work including the possibilities for mutual exchange. Establishing new exchange formats and with close monitoring of delays and implications, the ARTEM management and partners were able to limit the implications on project objectives and outcomes to a minimum. The great efforts of all involved partners to achieve the overall project goals in time and budget are greatly appreciated.

3. Activities and Achievements in Detail

The following paragraphs highlight ARTEM activities and achievements sorted in a sequence which follows mainly the work package and task sub structure. Only brief explanations of work and/or major achievements are listed with some key references provided, which should provide access to the more-in depth description of work performed and results. Contact details including the short name of the ARTEM partner and a contact person is named (usually a principal researcher with permanent contract with this institution having served as supervisor) to allow getting into contact for further inquiries. However, it should be noted, that large part of the research was conducted by colleagues not named, but being authors or co-authors of respective publications.
If a Technology Readiness Level (TRL) is given, this gives an approximate indication of the status of the technology at the project end as appraised during the final ARTEM assessment review.

In case of missing information or links, the former project coordinator will assist where possible.

3.1. Novel Liner Concepts

One of the great challenges for the air transport is the further improvement in energy (fuel) efficiency and the reduction of emissions. While in past years, the increase of engine size and bypass ratio has yielded significant positive contributions to both design goals, it involves a crucial noise issue too: larger engines emit low frequency noise (tones and broadband noise) while the well-established noise absorbing structures (liners) mounted in the inner duct of the engine nacelle are limited in their effectiveness due to limitation in size when trying to adjust to these changing requirements. In ARTEM, several concepts have addressed this issue aiming for low frequency and broad-band absorption.

Multifocal and Slanted Septum Liner (SOTON → Alan McAlpine), TRL 4

At Southampton university (SOTON), liner structures with additional degrees of freedom by adding sophisticated inner structures to the basic liner cell have been investigated. Additive manufacturing opens up new fields of complicated structures which have not been -technically and/or economically- possible before.
While the acoustic modelling and design of novel cell structures (as shown in Figure 2) is only the starting point, first measurements in Kundt tube have been made to further qualify the concept. Following steps included specific tests at Southampton and the NLR grazing flow facility.
Further, the manufacturing process and the assessment of printing quality for the small structures and the covering perforate structure are of high relevance for the successful application and have been examined carefully by the involved partners NLR and SOTON.

<u>Status at project end:</u> Modelling and testing have been described. Both concepts showed very good performance over the expected frequency range in grazing flow tests (NLR test).

<u>Future Work:</u> Maturation and large-scale testing for TRL increase is strongly recommended.

- *"Assessment of novel acoustic liners for aero-engine applications with sheared mean flow", Suresh Palani (SOTON), 28th AIAA/CEAS Aeroacoustics Conference. 14 June 2022 - 17 June 2022. Southampton, https://doi.org/10.2514/6.2022-2900,*
Green OA: https://eprints.soton.ac.uk/469594/

- *"Slanted septum and multiple folded cavity liners for broadband sound absorption", Suresh Palani (SOTON), International Journal of Aeroacoustics, vol. 20, 5-7: pp. 633-661. First Published June 9, 2021, https://doi.org/10.1177/1475472X211023835,*
Gold Open Access

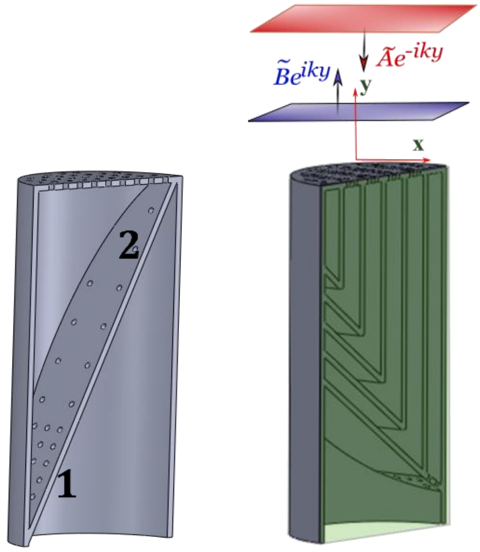


Figure 2: SOTON liner cell concepts for improved acoustic absorption. Left: Diagonal Septum Core ("Slanted Septum"), right: MultiFOCAL concept. *(© SOTON 2019)*

Zero Mass Flow Liner (DLR → Karsten Knobloch), TRL 3

In order to obtain the desired low frequency and broadband damping, an acoustic excitation of a cavity is used, which produces a periodic (zero net mass flow) in- and outflow through the perforation. In turn, this provides damping of the acoustic field in the main duct. The strength of the acoustic excitation can be used as impedance control to adjust for varying operating conditions (e.g. grazing flow velocity or sound pressure level)

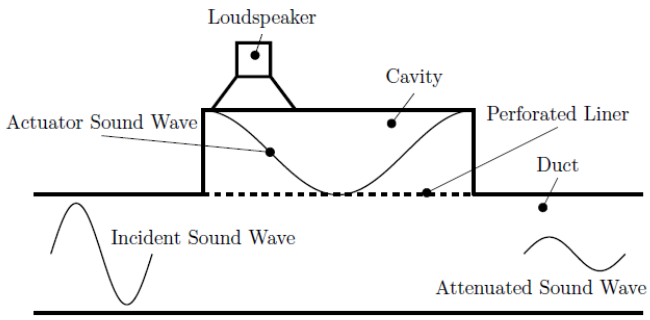


Figure 3: Zero Mass Flow concept by DLR. *(© DLR 2019)*

Status at project end:
Modelling and testing have been described. Concept showed good performance over the expected frequency range in grazing flow testing (NLR test) with some short-comings.

Future work: High levels of excitation need to be realized when applied under high grazing flow, high SPL conditions. An assessment/suppression of propagation of cavity excitation into main duct is needed.

- *"Effects of a secondary high amplitude stimulus on the impedance of perforated plates", Ralf Burgmayer (DLR), Journal of the Acoustical Society of America (JASA), J. Acoust. Soc. Am. 149 (5), May 2021, https://asa.scitation.org/doi/full/10.1121/10.0004951,* ***Gold Open Access***

- *"Reduction of inertial end correction of perforated plates due to secondary high amplitude stimuli", Ralf Burgmayer (DLR), JASA Express Lett. 2, 042801 (2022); https://doi.org/10.1121/10.0009920* ***Gold Open Access***

Sandwich panel with friction powder (COMOTI → Constantin Sandu), TRL 3

A conventional liner structure is used, where the cavities are filled with powders of different material. The friction between the powder particles adds to the acoustic losses encountered by the general liner structure. A large variety of powders was tested in Kundt tube and low speed wind tunnel (CNRS), with best absorption found for cork, Formalux, balsa wood powder, polystyrene balls, and fluff of bird.

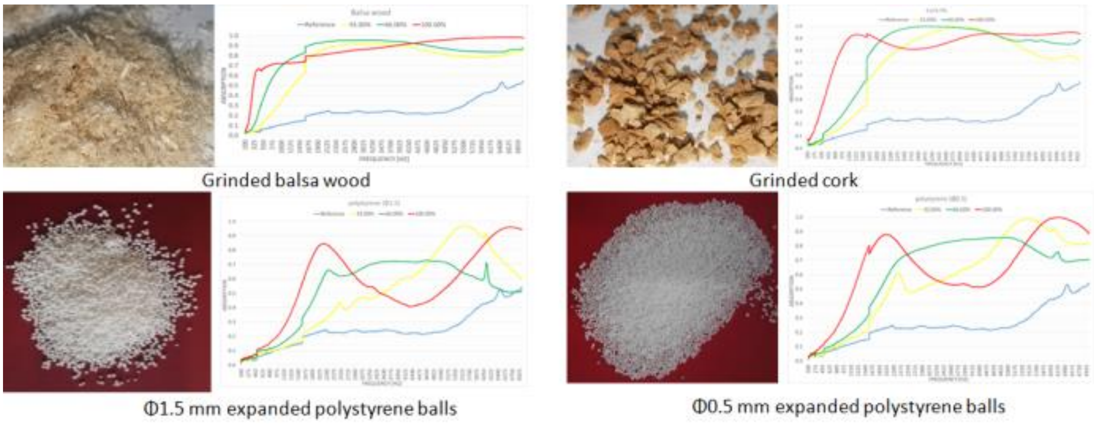


Figure 4: The best selected powders.

Cork at 66% filling height showed superior performance. Testing of cork powder liner in NLR wind tunnel with high porosity covers (20-30%, partly with additional mesh) showed overall noise reduction below 3dB for most combinations of flow velocity, incident sound direction (upstream/downstream) and liner configuration, with peak values up to 10dB (500Hz, M=0.4). The powder tended to shift between cavities due to insufficient internal cavity sealing during test at NLR.

<u>Status at project end:</u> Testing has been successfully accomplished. Concepts showed good performance over the expected frequency range in grazing flow testing (NLR test).

<u>Future Work:</u> Long-term stability of powder size/consistency not addressed, ingestion/absorption of fluids and drainage not addressed – not even on concept scale. No generalized description of “best powder” available (e.g. grain size, density, amount).

- *“Innovative liner concept using friction powder for increasing of broadband noise absorption. Applications for broadband noise absorption in fan duct, reduction of jet noise reflected by wing pressure side and noise reduction in aircraft cabin.”, Constantin Sandu (COMOTI), 11th EASN Virtual International Conference on Innovation in Aviation & Space to the Satisfaction of the European Citizens / 2022 IOP Conf. Ser.: Mater. Sci. Eng., Paper No 012049, vol 1226, https://doi.org/10.1088/1757-899X/1226/1/012049* **Gold Open Access**

Plasma Actuator (EPFL/AEDS → Herve Lissek), TRL 3

Two active noise attenuation methods, called “Hybrid absorption” and “Active impedance control” were developed. Both are plasma-based actuators for active sound absorption.
The hybrid absorption technique employs a passive porous layer in front of the actuator. Applying active pressure cancellation to the plasma actuator located behind the passive layer, the system imposes an acoustic condition with impedance equal to the layer resistance. Alternatively, the active impedance control method does not have any passive absorbing layer. Two microphones located in front of the actuator estimate the acoustic pressure as well as the particle velocity in the vicinity of

the actuator, thus estimate its acoustic impedance. The estimated impedance is then compared with a target one. The error (difference between target and estimated impedances) is used as a feedback signal to the plasma actuator to adjust the impedance towards the desired value.

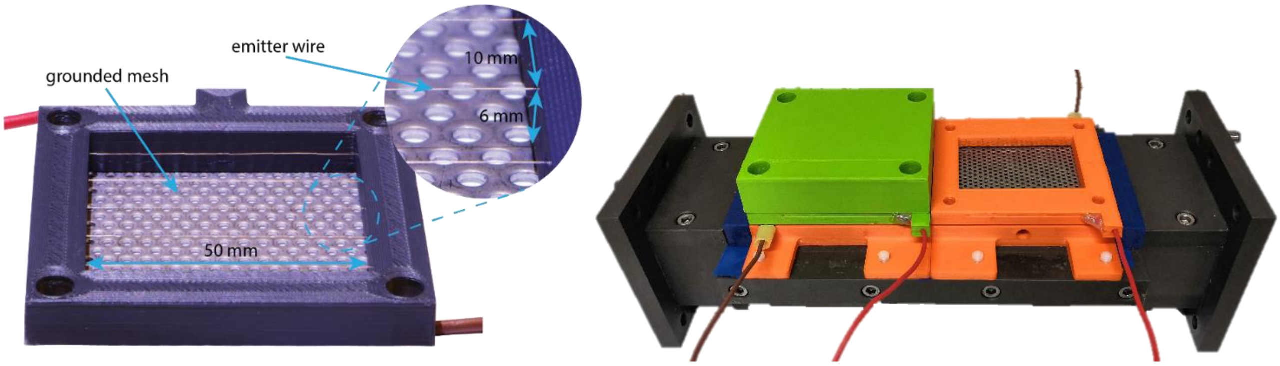


Figure 5: One cell plasma actuator (left) and two cell plasma liner prototype in a duct section

Both strategies were first tested under the normal sound incidence in an impedance tube. After these preliminary tests, two specific absorber cells were designed for the operation under grazing incidence, which had minor changes in the construction compared to the normal incidence case.
The tests at CNRS facility were performed with both plasma-based actuators. Hybrid absorption and active impedance control have shown their capability to attenuate noise under grazing incidence. Due to their fundamentally different behaviours, and to different performance in various cases, one control strategy can be preferred to the other in certain situations.
The result of a transmission loss measurement for the plasma actuator (hybrid absorption) showed over a large frequency range (100-1500Hz) significantly increased absorption (>20dB) compared to the passive case.
However, this impressive result was limited to the no flow case so far. The turbulent noise interfering with the actual signal on the control input microphone and the limited output power of the plasma actuator control decrease the performance for SPL>95dB.
Following the CNRS test, further development was performed to address the identified limitations.
A very nice demonstration of the corona discharge concept for a slightly different application was realized and is found at: https://youtu.be/-7Eemh63NcA.

Status at project end: A modified control strategy was implemented to increase the sound pressures that the concept can work at. The geometry of the actuator has been revised in order to increase the output acoustical power. The design of a high voltage amplifier was proposed, and a two-channel prototype was assembled to make a compact, low cost, and lightweight amplification of corona discharge-based actuators, which can be an alternative to the existing laboratory amplifiers.

Future Work: Prove of enhanced capabilities in a further grazing flow test.

- *"Development of a plasma electroacoustic actuator for active noise control applications", Stanislav Sergeev (EPFL), Journal of Physics D: Applied Physics, Vol.53, Number 49, https://iopscience.iop.org/article/10.1088/1361-6463/abafde,* **Gold Open Access**

- "Feedback impedance control for sound absorption with corona discharge actuator", Stanislav Sergeev (EPFL), Euronoise 2021, **Green OA:** Paper No 270, http://ftp.sea-acustica.es/fileadmin/Madeira21/ID270.pdf

- *"Corona Discharge Actuator as an Active Sound Absorber under normal and oblique incidence", Stanislav Sergeev (EPFL), Acta Acustica, Vol. 6, 2022, number 5, https://doi.org/10.1051/aacus/2022001,* **Gold Open Access**

Semi active liners (CNRS/LAUM → Yves Auregan), TRL3

With the basic idea to study the benefit of moving parts in conjunction with liner structures, several structures were manufactured and tested. For the “beam array liner” (Figure 6), microstructures with micro-cuts in a thin titanium plate (0.1 mm) were manufactured. They allow a high flexibility and large motions of a moving mass. It was experimentally verified that the addition of a moving mass significantly decreases the operating frequency of a resonator and paves the way for the use of this concept. This system has been mechanically and acoustically characterized under normal incidence in order to be compared with an analytical model, showing a very good agreement between the measurements and the model for a unique beam. An array of these beams has been mounted in the wall of the CNRS/LAUM test bench with grazing flow. It was shown that this device has a strong potential to absorb sound over a very wide frequency range, starting at low frequencies. But it can also be seen that negative absorption (sound amplification or whistling) occurs. Further studies are therefore needed to investigate the stability problems of this high potential concept.

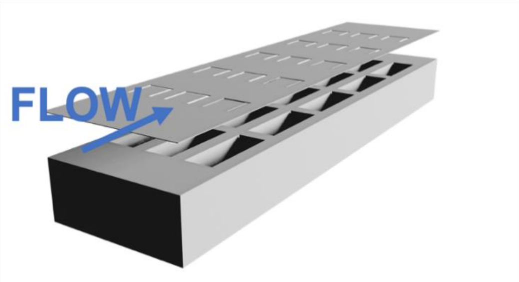


Figure 6: “Beam-array” liner concept

Status at project end: Several concepts based on “moving mass” principle suggested and tested in normal incidence and grazing flow setups. Analytical modelling available

Future Work: Optimize concepts and address detrimental effects (sound production, application in environment with hydrodynamic pressure fluctuations, high SPL effects)

Liner modelling by Meta Materials (U Roma3 → Umberto Iemma), TRL 3

Starting from the connection between Standard Transformation Acoustics (ATA) and PGMS exploiting the Generalized Snell's Law (GSL) for acoustic reflection and refraction, during the ARTEM project, acoustic treatments were developed for the air intake of a turbofan engine for the realization of the so-called virtual scarfed inlet and improving the acoustic shielding performance of BWB configurations with engines installed on-top of the centre body.
An essential feature of the proposed model is the absence of dissipation mechanisms: the phase gradient metasurfaces allow for a redistribution of the acoustic energy by controlling the phase of the scattering field through purely reactive effects. From a numerical point of view, the equivalent metafluid model has brought significant benefits in terms of computational effort, making feasible (robust) optimization activities that are fundamental in the conceptual design phases.

Further, a metafluid model could be established as description for various meta-materials useful for numerical simulations. The activities within ARTEM were built on results of the H2020 project AERIALIST.
The metafluid model reached a good agreement with the reference simulations in the tested cases, both for the exterior acoustics benchmark and the duct acoustics one. The lossy metacontinuum proved to be effective in predicting the viscous and thermal effects within the thin channels of some of the tested cells, providing results in good agreement with classic approaches. Even if its derivation generally involves the calculation of the equivalent impedance of the cell, the use of the

metacontinuum offers some numerical advantages compared to the equivalent impedance method when applied to the evaluation of the transmission coefficient in a duct.

- *"Radial Basis Functions for Stochastic Metamodels Tailored to Aeroacoustic Applications", Umberto Iemma, 25th AIAA/CEAS Aeroacoustics Conference 2019, 20.-24.05.2019 Delft/ The Netherlands, https://doi.org/10.2514/6.2019-2746*

- *"An integrated toolchain for the design of aeroacoustic metamaterials: the H2020 project AERIALIST", Umberto Iemma (URoma3), InterNoise21, Washington, D.C., USA, INTER-NOISE and NOISE-CON Congress and Conference Proceedings, pages 1945-2948, pp. 2699-2707(9) https://doi.org/10.3397/IN-2021-2207*

Liner modelling in the time domain (ECL → Didier Dragna)

ECL has developed a numerical methodology to account for extended-reacting liners such as conventional porous materials or metamaterials in time-domain simulations. A schematic of the problem is shown in Figure 7. The liner is modelled by an equivalent fluid and the propagation of the acoustic waves in the liner is accounted for by solving the equivalent fluid equations. As the density and the compressibility of the liner depend on the frequency, a direct translation of the equivalent fluid equations in the time domain would lead to convolutions, whose computation is cumbersome. This difficulty is tackled by approximating the density and compressibility by a rational function of the frequency.

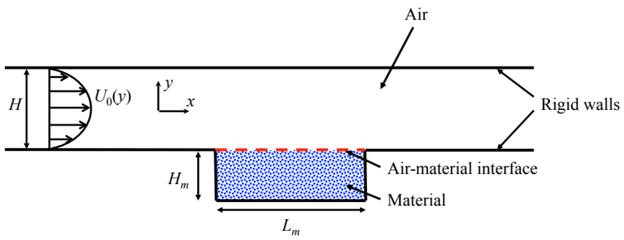


Figure 7: Liner setup in duct

This allows to replace the convolution by an additional set of differential equations that can be solved using standard numerical methods. The method has been implemented in a finite-difference time-domain (FDTD) solver. It has been validated against a one-dimensional test-case for different types of liner, corresponding to a transmission problem of a pulse at an interface with a material and for which an analytical solution is available. In a second part, ECL has investigated the possibility of obtaining the rational approximation of the density and compressibility of the material from measurements, without having to rely on an analytical model. The idea is that, while there are very accurate models such as the Johnson-Champoux-Allard-Lafarge for porous materials, analytical models may not be available for innovative liners. For this, a Kundt tube is employed and the density and compressibility are determined with the transfer function method. Once the density and compressibility are obtained, a rational function approximation is calculated using optimization methods. The feasibility of the method has been demonstrated using standard porous materials, double-porosity materials as well as 3D-printed materials. In particular, a small number of poles was sufficient in all cases to accurately approximate the density and compressibility determined with the transfer function method over a very wide frequency band.

- *"Pole identification method to extract the equivalent fluid characteristics of general sound-absorbing materials", Antoni Alomar (ECL), Applied Acoustics, Vol. 174, 107752, doi:10.1016/j.apacoust.2020.107752,* ***Gold Open Access***

- *“Time-domain simulations of sound propagation in a flow duct with extended-reacting liners” Antoni Alomar (ECL), Journal of Sound and Vibration, Vol. 507, 116137, doi: 10.1016/j.jsv.2021.116137* **Gold Open Access**

Liner Testing (CNRS → Yves Auregan / NLR → Kylie Knepper):

Comparative testing of more-explorative and still lower TRL 2050 liner concepts has been performed in the wind tunnel of LeMans University (CNRS). Here, beside the semi-active liners of CNRS, the liner structures filled with different powders (COMOTI concept) were. Prior to this test campaign, the plasma-actuator based active liner structure developed by EPFL (supported by simulations of AEDS) was tested in the same facility.

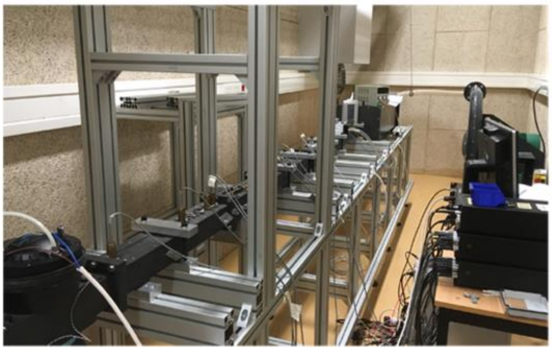


Figure 8: CNRS/LAUM test bench for grazing flow tests

The full-scale liners that were made by means of additive manufacturing have been tested at the NLR Flow Duct Facility (FDF, Figure 9) along with the NLR reference liner (NLRA2), the ZML from DLR, and the powder liner from COMOTI with good results. ISVR reported good agreement with the liner predictions for the MultiFOCAL and the SSC for Mach 0.3.

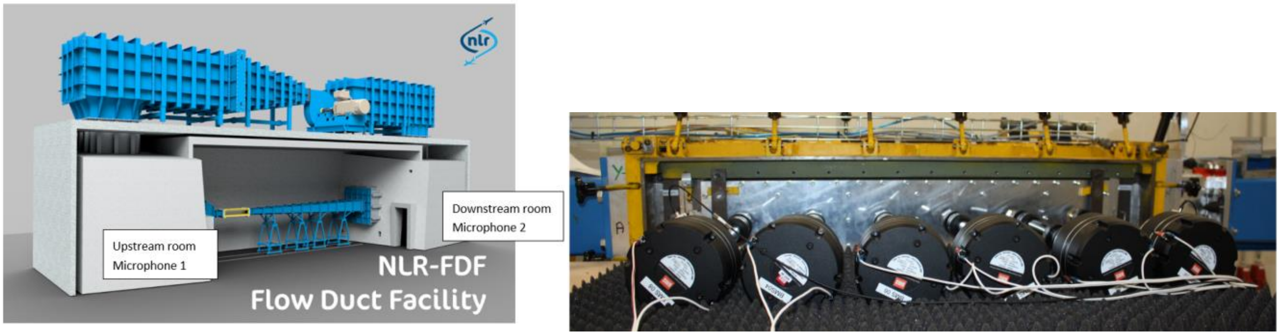
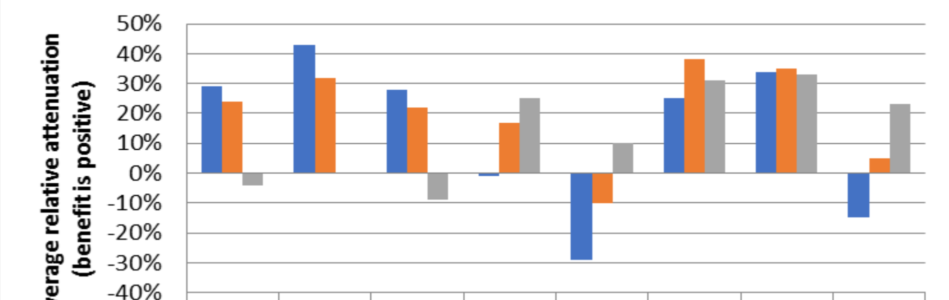


Figure 9: FDF test rig for high-speed testing of liners (left) and ZML-liner setup at FDF test section (right).

Liner Performance Assessment (RRD → Christoph Richter)

Beside the support on specifications and continuous progress monitoring of development, RRD has facilitated a final assessment of some promising liner technologies.
Data on liner benefits have calculated for two different conventional tube and wing aircraft platforms, a wide body aircraft with underwing engine installation, and a Business jet with tail mounted engine installation. All novel liners must be considered not fully optimised for the respective platforms. The assessment is based on the impedance provided by SOTON for the MULTIFOCAL (MFC) and Slanted Septum Core (SSC) concepts, and by DLR for the ZML concept (results for widebody configuration in Figure 10).



	WB-I-SSC4	WB-I-SSC6	WB-I-MFC6	WB-B-SSC4	WB-B-ZML4	WB-B-SSC6	WB-B-MFC6	WB-B-ZML6
Approach	29%	43%	28%	-1%	-29%	25%	34%	-15%
Cutback	24%	32%	22%	17%	-10%	38%	35%	5%
Sideline	-4%	0%	-9%	25%	10%	31%	33%	23%

Figure 10: Relative benefit of the novel liner options for the Wide Body evaluator platform (Average in the frequency range of 500 Hz to 6400 Hz relative to datum for Bypass duct –B and -SSC4 for the inlet -I and 60 mm deep SDOF for the other, 60 mm deep novel inlet liner options –-SSC6 and –I-MFC6.

Acoustic installation effects for UHBR turbofans (SOTON)

The objective of this work was to use theoretical analysis to model the refractive effect of the boundary layer. This necessitated the use of model "boundary-layer" profiles in order to derive analytic solutions. Starting with the simplest model profile - the step-function – analytical solutions have been identified. Further, a new theoretical solution for the linear shear profile has been completed. In this case, it is necessary to solve the Pridmore-Brown equation for the sound field in the shear flow region. The Pridmore-Brown equation is derived from the linearised Euler equations, for a parallel shear flow. An approximate solution is derived for the Pridmore-Brown equation by taking an inner asymptotic expansion that is valid for sufficiently thin boundary layer thicknesses relative to the radius of the cylindrical fuselage. Finally, results were compared with numerical results using a $1/7^{th}$ power law for the boundary layer – finding very good agreement with the analytical solution based on the linear profile, when the boundary layer shape factor is matched.

Furthermore, the methods have been extended to calculate the far-field directivity. The amplitude of the far-field radiated noise is the same comparing simulations with uniform flow or including the boundary layer. However, there are significant differences in the phase of the directivity for multi-modal source distributions radiating to the far-field.

Status at project end: New analytical methods have been successfully developed that deliver a fast and efficient engineering model for predicting installation acoustic effects for fan noise radiated from Ultra High Bypass Ratio turbofan aero-engines.

Future Work: no comment

- *"Theoretical Methods for the Prediction of Near-Field and Far-Field Sound Radiation of Fan Tones Scattered By A Cylindrical Fuselage", Dionysios-Marios Rouvas (SOTON), 27th AIAA/CEAS Aeroacoustics Conference (part of AVIATION 2021), 2.-6.August 2021, https://doi.org/10.2514/6.2021-2300*, **Green OA:** https://eprints.soton.ac.uk/468266/

- *"Prediction of Fan Tone Radiation Scattered By A Cylindrical Fuselage", D. Rouvas (SOTON), 11th EASN Virtual International Conference on Innovation in Aviation & Space to the Satisfaction of the European Citizens / 2022 IOP Conf. Ser.: Mater. Sci. Eng., Paper No 012050, vol 1226, https://iopscience.iop.org/article/10.1088/1757-899X/1226/1/012050,* ***Gold Open Access***

- *"An analytical model of sound refraction by the fuselage boundary-layer for fan tone radiation from a turbofan aero-engine" Dionysios-Marios Rouvas (SOTON), 28th AIAA/CEAS Aeroacoustics Conference. 14 June 2022 - 17 June 2022. Southampton, https://doi.org/10.2514/6.2022-3059,*

3.2. Shielding Modeling

Influence of mean flow on shielding (DASSAV → Stephane Lemaire)

Dassault Aviation has developed a numerical methodology to assess the shielding effects of inlet fan noise by the main wing of a Falcon 7X business jet, taking into account the impact of a viscous mean flow. The methodology relies on the resolution of the Linearized Navier-Stokes equations around an averaged viscous mean flow, with the in-house code AETHER. The computational strategy has been adapted to reach the highest frequencies (up to 1600 Hz) by optimizing the size of the computational domain using a truncated aircraft geometry and an absorbing viscosity law next to the computational boundaries. Results show a strong acoustic fan shielding by the main wing (below the aircraft) for the highest frequencies (between 5 and 15 dB). Moreover, installation effects indicate that the shielding is stronger at the considered frequencies, by about 5 dB, when taking into account the non-uniform viscous mean flow.

Status at project end: Models improved and tool chain validated, simulations achieved.

Future Work: Further work will be needed to improve and consolidate the current methodology. The use of a high-order solver to reduce the number of mesh nodes per wavelength is needed to predict the installation effects at higher frequencies, relevant to engine fan noise, with AETHER code.

Geometrical Theory of Diffraction – GTD (TSAGI → Victor Kopiev)

For the correct shielding efficiency calculation, where the amplitude and phase characteristic are important, a reliable diffraction calculation method is required. The Geometrical Theory of Diffraction (GTD), or Uniform Theory of Diffraction (UTD), is chosen as calculation tool because it meets the abovementioned requirements and is computationally cheap enough. Initially, GTD was developed for the case of infinite halfplane sound diffraction calculation but it can be generalized for the case of screens of various shapes. The calculation results demonstrate that the use of the GTD-based shielding calculation method allows obtaining information about the geometrical, diffracted field and total field distribution as well as the phase and shielding efficiency distribution in the case of rectangular and flat polygonal screens (of BWB-like form, Figure 11) at different observation points.

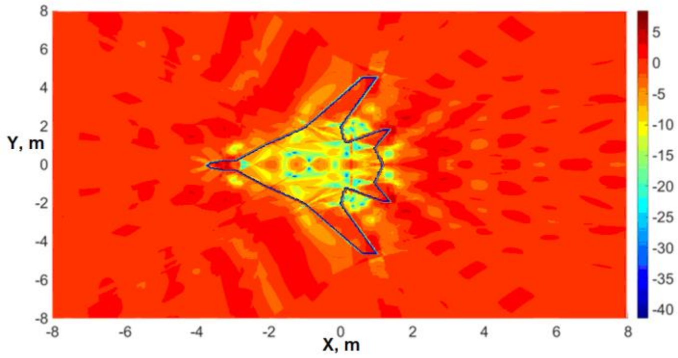


Figure 11: Shielding efficiency distribution (in dB) for a time-harmonic monopole source located above a planar polygonal screen of BWB-like shape.

A method to obtain the optimal power plant position on a BWB relative to the airframe from the point of view community noise reduction has been proposed. For a simplified example, it has been shown that for the climbing and approach regimes of the BWB aircraft it is possible to find engine positions providing maximal shielding efficiency in the first approximation of the GTD.

Status at project end: Model improved and validated. Measurements, performed in an anechoic facility, have allowed to enhance the noise source representation and validate the analytical tool.

- *Assessment of Shielding Effect Effiency for BWB with UHBR, Victor Kopiev (TSAGI), Aerospace Europe Conference AEC2020, 25-28 February 2020, Bordeaux*

Final note on reported activities for Liners and Shielding Modeling

The work on meta-materials as other work in WP1 (improvement of noise scattering prediction due to shear flow/boundary layers, shielding prediction tools, liner modelling in the time domain) aims at improved prediction capabilities. Here, a direct benefit in terms of noise reduction cannot be given, without a specific application selected.
Nevertheless, the improvements made in WP1 will be very useful in future project work and have consistently been published in order to advance the general knowledge of the community.

Note on reported activities for Assessment of Noise at the Source and Associated Reduction Means

The following activities presented in sections 3.3. - 3.7. investigate the noise reduction at the source, focusing particularly on aircraft installation effects. These are either due to flow interactions with the airframe or engines, so called aerodynamic installation effects, or to the scattering of sound waves by the airframe, known as aeroacoustics installation effects.
Since these phenomena are inevitably encountered on both conventional and new aircraft architectures, it is mandatory to address them in order to manage the emitted noise and limit its impact on the ground, especially for future air fleets. The main objectives of this activities are to assess these acoustic sources and investigate reduction solutions, either through geometrical modifications or new technology systems.

3.3. High Lift Device Noise

A Numerical Benchmark Exercise Prepares Noise Reduction Investigations

For a cross-comparison study of different numerical tools and tool chains of three ARTEM partners (ONERA, Technical University of Braunschweig (TUBS) and DLR), the Leisa2 F16 high-lift configuration, jointly specified by ONERA/DLR as the Category 6 problem of the Benchmark for Airframe Noise Computations (BANC) workshop, has been selected.

For this configuration a comprehensive experimental database is available from earlier aerodynamic and aeroacoustics measurements conducted in the ONERA F2 and DLR AWB wind tunnel facilities.

Very good agreement between all simulations is obtained in terms of spectral shape and level yielding differences of the order of 2dB. This indicates that all methods provide a similar spectral content close to the slat trailing edge, as indicator of properly catching the important slat noise sources.

2D-design study (DLR → Roland Ewert)

A 2-D design study has been carried out by DLR using 5 different high-lift profiles: a conventional slat (reference) with various gap/overlap slat settings, a Very Long Chord Slat (VLCS), and two novel Krüger slat designs. CAA and CFD simulations have been conducted using 3 different velocities. Acoustic simulations are carried out using an APE-4 based acoustic analogy with stochastic sound sources realized by the Fast Random Particle-Mesh (FRPM) method. The computational time of the hybrid approach is about 10 core hours for RANS CFD (background flow field and source turbulence statistics), and typically 20 core hours for the CAA part with the Discontinuous Galerkin Code DISCO. Acoustic results (narrow band spectra) and time averaged aerodynamic characteristics (cp-distribution) of the 2-D design study have been cross-compared for the F16 reference profile with the scale resolving approach applied before by DLR. Good agreement for both data sets could be demonstrated. For the F16 reference profile a gap/overlap slat setting variation study has been performed. With the Very Long Chord Slat (VLCS) variant a low-noise geometry has been studied that intends to lower noise emissions relative to the F16 reference profile by shifting the position of the slat trailing edge above the upper main element of the wing. Two novel Krüger flap designs have been evaluated concerning their noise reduction trends.

The VLCS yields an OASPL noise reduction potential of up to 6dB towards the ground, as was found in previous experimental studies.

The Krüger flap designs yield the clearest noise reduction potential. Presumably, due to the missing recirculation area and free shear layer impingement on the lower slat surface that otherwise is always present for the conventional slat designs.

For the first considered Krüger design (namely the F11 conf1), the OASPL noise reduction yields on average 6dB over the entire lower polar arc range (between 180° and 360°). The aerodynamically optimized Krüger design, however significantly loses part of the noise reduction potential, thus indicating the importance of a holistic high-lift design that includes besides aerodynamic characteristics also an appropriate noise metric into the cost function used for optimization.

Status at project end: Meaningful noise trends and clear noise reduction potentials could be identified using fast 2-D design studies. Conventional slat noise is found to scale with the fourth power of Mach number. A small overall noise reduction could be found in the overlap variation study of the order of 1dB. The gap variation study revealed clearer noise reduction potential yielding about 3dB in OASPL radiation towards the ground.

- *“Towards Wall-Modeled LES with Lattice Boltzmann Method for Aeroacoustics: Application and Understanding” F. Soni (DLR), 28th AIAA/CEAS Aeroacoustics Conference. 14 June 2022 - 17 June 2022. Southampton,* https://doi.org/10.2514/6.2022-2918

Slat geometry modification (ONERA → Marc Terracol)

In this task, ONERA’s aimed to study noise reduction concepts based on trailing edge serrations for slat noise reduction. Considering the possible geometrical complexity of the serrations, ONERA’s approach relies on the zonal use of an Immersed Boundary Condition (IBC) approach on a classical body-fitted grid. The reference baseline case is the LEISA2 three-element F16 airfoil, at an inflow velocity of 61.5 m/s and an angle of attack of 6.15°. Several simulations dealing with serrated configurations were computed, where the serrated slat cusp is accounted for using the IBC approach, using appropriate source terms in the Navier-Stokes equations to model the presence of solid walls. The serration patterns are introduced at the slat cusp (see Figure 12), with the general idea of triggering a faster transition of the shear layer to turbulence and possibly lead to an eddy breakup towards smaller, less energetic, scales.

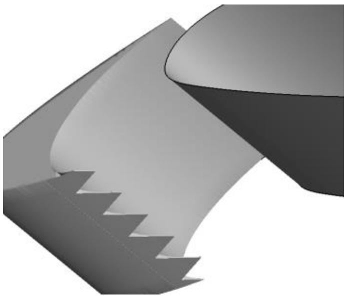


Figure 12: Slat serrations location

It was noticed that the RMS quantities are significantly affected by the serrations: all serration shapes appear to increase the level of TKE, just downstream of the slat cusp, where 3D structures are generated and turbulence production is increased. Compared to measured data, the acoustic spectrum agrees very favourably, except of a tonal component (around 2kHz) – caused by an aero-acoustic feedback loop - which is missing in the simulated data.

Status at project end: In summary, the study on serrated slats showed that while the slats do not change the aerodynamic performance of the high lift device. They potentially enhanced mixing of the shear layer over the slat cavity, but did not significantly change the aeroacoustic characteristics of the slat and high lift device.

Noise reduction using microscale surface treatments (U Bristol → Mahdi Azarpeyvand)

The purpose of this task was to evaluate the effectiveness of surface finlets as a passive tool for reducing trailing edge and slat noise. To study the use of microscale surface treatments for the reduction of trailing edge noise for lifting devices, a series of tests have been carried out. A variety of finlets were designed and tested on a flat plate (zero-pressure-gradient) and different aerofoils. The experiments were conducted in the aeroacoustics facility of the University of Bristol, which is anechoic above $160\,Hz$. Tests were carried out over a wide range of velocities, corresponding length-based Reynolds number range of $Re\ =\ 660{,}000$ - $1{,}320{,}000$ for the flat plate and chord-based Reynolds number of $Re\ =\ 400\,000$ for the NACA 0012 aerofoil. A beamforming array, with 73 microphones, was mounted over the test section for locating the noise sources and the measurement of the radiated noise.
The far-field noise measurements have confirmed that the surface finlets can reduce trailing edge noise by approximately $5\ dB$ in the case of the NACA 0012 aerofoil and $3\ dB$ for a flat plate. Various near-field measurements, namely surface pressure fluctuations, spanwise coherence, p-u coherence, etc, have also been successfully tried, which helped better understand the underlying physics of trailing edge noise reduction. Over 50 different finlets were designed and tested as part of these large experimental campaign. For selected geometries, detailed hotwire measurements were carried out upstream, within, and downstream of the finlets. The velocity and surface pressure measurements were carried out synchronously, enabling a pressure-velocity coherence analysis.

Status at project end: A range of surface treatments were examined experimentally on a flat plate, NACA0012 and a 30P30N HLD. The results have shown the capability of finlets for reducing he far-field noise. The mechanisms through which noise reduction is achieved were found to be complex. The finlets were found to reduce the surface pressure fluctuations through channelling of the boundary layer structures, altering their spanwise coherence, increasing mixing and lifting of the structures away from the surface.

- *"Investigations on the Application of Various Surface Treatments for Trailing Edge Noise Reduction on a Flat Plate", Felix Gstrein (U Bristol), 27th AIAA/CEAS Aeroacoustics Conference, AIAA 2021-2263, https://arc.aiaa.org/doi/10.2514/6.2021-2263,* **Green OA:** https://research-information.bris.ac.uk/en/publications/867a75f1-843e-472f-8f6a-cfbe032e2a99

- *"Turbulence Characteristics Related to Finlet Application for Trailing Edge Noise Reduction of a NACA 0012 Airfoil", Felix Gstrein (U Bristol), 27th AIAA/CEAS Aeroacoustics Conference, AIAA 2021-2112, https://doi.org/10.2514/6.2021-2112,* **Green OA:** ***https://research-information.bris.ac.uk/en/publications/a22925b9-5111-4ff1-b612-48053d935fef***

- *"Airfoil Trailing Edge Noise Reduction by Application of Finlets", Felix Gstrein (U Bristol), AIAA Journal, Vol. 60, No. 1, January 2022, https://arc.aiaa.org/doi/10.2514/1.J060699*

Noise reduction by LES optimization (TU BS → Rinie Akkermans…now HAW Hamburg)

In this task, TUBS carried out LES simulations for NACA0012 with and without surface treatments. Based on U Bristol wind tunnel studies, a promising finlet design was suggested for the current high-fidelity numerical investigation. The numerical simulations aimed to provide numerical insight into the noise reduction mechanism of the finlets based on the near-field data and also validate the results with the experimental findings.

The simulations performed follow the “Overset-LES” approach. Overset-LES is a zonal hybrid RANS-LES method, where the Perturbed Compressible Navier Stokes equations (PCEs) are solved on a steady background flow derived from an a-priori RANS. The onset of turbulence for the zonal method at the RANS-LES interface is provided by Fast Random Particle Mesh method (FRPM). The synthetic turbulence is coupled to the momentum equation using an Eddy Relaxation Term (ERT). Two RANS and Overset-LES were performed: i) baseline configuration of NACA0012 and ii) NACA0012 with 2D streamwise finlets, mounted upstream of the trailing edge. The finlets are mounted on both, pressure and suction sides of the profile. The simulations (Figure 13) were carried out at a free-stream velocity of 20m/s, a chord-based Reynolds number, 4.2×10^5, and an angle of attack,
$\alpha = 4°$. The RANS computations were performed using the DLR’s 2nd order accurate finite volume code “TAU” and the Overset-LES are carried out using the 4th order accurate “viscous-PIANO” code.

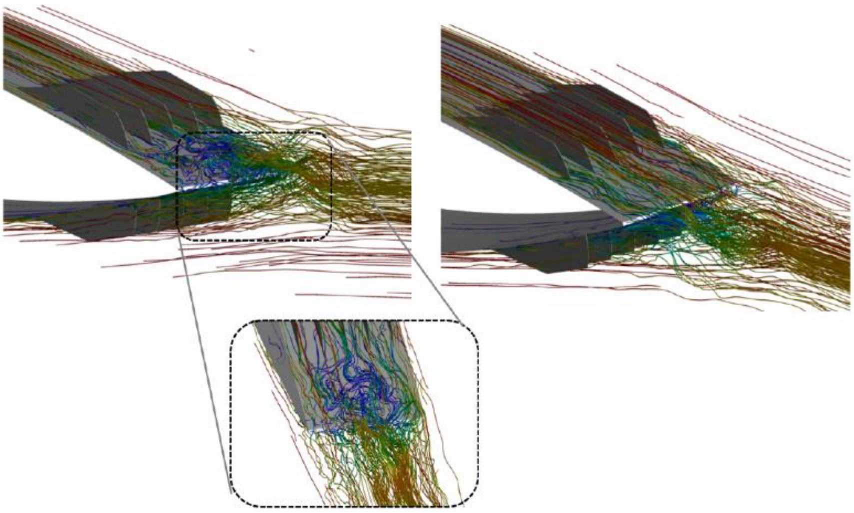


Figure 13: Near-wall instantaneous streamlines coloured with the magnitude of the total velocity on the suction and the pressure side.

The unsteady flow features of the baseline and the finlet configuration obtained from the Overset-LES were validated with the experimental data provided by University of Bristol. The Power Spectral Density (PSD) of the surface pressure fluctuations (ϕ_{pp}) showed good agreement with the experimental data. The finlets offer additional wetted area for the flow and hence induces dissipative effects, which is seen in the high-frequency range of the PSD spectrum. In the finlet wake mixing effects between the turbulence structures from the different finlet channels and structures shed from the top of the treatment are apparent.

Status at project end: The results demonstrated the capability of the Overset-LES approach in accurately predicting the noise reduction potential of surface treatments applied on an airframe component. Furthermore, the findings indicate that the noise reduction mechanism of finlets is related with dissipative effects induced wall friction along the finlet walls and turbulence mixing in the finlet wake.

- *Hybrid Overset-LES Simulations of Noise Reduction Concepts of Loaded Airfoils, Paul Bernicke (TU BS), ISROMAC 18, Online 23.-26.11.2020 (postponed from 19.-23.04.2020, Honolulu/Hawai, USA), to be published in IOP Science series, Journal of Physics: Conference Series*

- *"Trailing-edge noise reduction of a wing by a surface modification", V. Ananthan (TUBS), InterNoise21, Washington, D.C., USA, INTER-NOISE and NOISE-CON Congress and Conference Proceedings, pages 2949-3943, pp. 3194-3201(8),* [*https://doi.org/10.3397/IN-2021-2326*](https://doi.org/10.3397/IN-2021-2326)

3.4. Jet Installation Noise

The emergence of UHBR engines provides significant jet noise mitigation, since the jet flow speed is reduced as the diameter is increased. However, the integration of these large turbofan engines into the airframe becomes more and more critical, due to the extreme proximity of the nacelle to the wing. In the high lift configuration of a conventional aircraft, the aerodynamic interference of the jet shear layer with the deployed flap generates a very loud source of excess noise, which may dominate over the generic jet noise.
Here, several approaches have been studied to mitigate the acoustic consequences of jet/flap interaction. The studied technologies are applied either on « Airframe side » (flap) or « Engine side » (nozzle) and are either passive or active. On « Airframe side », a classical thrust gate behind the jet, i.e. a cutout in the flap to avoid the interaction of the jet with the flap trailing edge is no real solution to the problem because the free flap side edges will again generate noise. Consequently, modifying some flap parameters is necessary, for example adding flap surface liners or changing flap deflection angle. On « Engine side », ARTEM has shown that the jet/flap interaction noise can be reduced via changing the jet nozzle (e.g. chevron or corrugated nozzle). Another promising way to reduce jet/noise has been assessed, based on the concept attributing its low frequency part to the instability waves scattering on the trailing edge.

Airframe side treatment for jet noise reduction (DLR → Roland Ewert)

2-D CAA design study

The RANS simulations of the installed jet case reveal a clear interaction of the deployed flap with the jet shear layer. For an increased flap deflection angle, increased levels of turbulence kinetic energy are visible at the flap trailing edge. In correspondence, the 2-D CAA jet noise studies reveal for the jet-flap installation effect a clear and expected trend with a reduction of the jet noise levels into the lower radiation arc with decreasing flap setting, i.e. with a reduced interaction of the flap geometry with the jet shear layer. The related airframe noise study reveals an opposite trend, where the flap noise contribution decreases with increasing flap angle. The reason for this effect could be traced back to an area of turbulence kinetic energy at the flap leading edge that is observed to increase at decreasing flap angle.

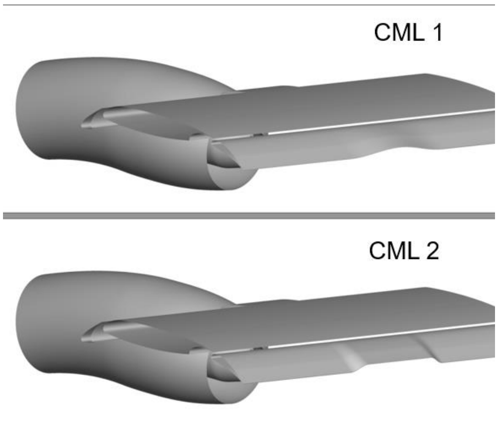


Figure 14: Continuous mould line designs

The reference and noise control technology that finally has been tackled can be summarized as follows:

a. reference configuration based on an unmodified high-lift system (potential trailing edge noise source)
b. porous trailing edge treatment (reduction of trailing edge noise via porous materials at flap trailing edge)

c. two continuous mould line configurations (jet-flap interaction avoided by means of continuously shaped thrust gate that avoids by design additional side edges, see Figure 14)
   - CML-1: continuously changing spanwise change of flap deflection over the width of the bypass jet
   - CML-2: constant flap deflection over a certain sub wing span and rapid adaption of deflection angle at the sub-domain boundaries to full flap deflection angle.

The porous design study reveals a clear noise reduction effect with porosity applied to the trailing edge relative to a solid reference flap. The influence of different types of porosities appears not to be significant for the types of materials studies. The effect of the extension of the porous area on noise was studied. For a 50% porous flap, slightly improved noise trends can be observed compared to a 25% porous flap.

3-D scale resolving zonal LES

In the resolved part of the spectrum, the comparison has shown that not both of the modified flap geometries yield a noise reduction. The configuration with mainly constant flap deflection (CML-2) has not shown any significant beneficial acoustic effect. The CML-1 configuration turned out to have potential for noise reduction in the low frequency range up to 1 kHz, with up to 2dB integrated OASPL noise reduction effect in the low frequency range. In the high frequency range, however, an increase in noise similar to CML-2 is observed. Somewhat in agreement with the 2-D design study, the reduction of the flap deflection lowers the immediate trailing edge noise source but simultaneously leads to extra flap leading edge noise that lowers the benefit of the retracted flap.

<u>Status at project end</u>: In general, the 2-D design study provides an estimate of the broadband noise contribution coming from both, airframe and jet-noise sources. It lacks the noise effect coming from the coherent jet noise structures that are mainly responsible for the “installation hump”, i.e. a local increase in the spectrum due to the interaction of the airframe with the jet.

Jet interaction with airframe structures (SOTON → Jack Lawrence)

In this task, a number of low-noise engine bypass nozzle geometries were designed, 3-D printed and tested at model scale in SOTON’s Doak Laboratory using their Flight Jet Rig (FJR).

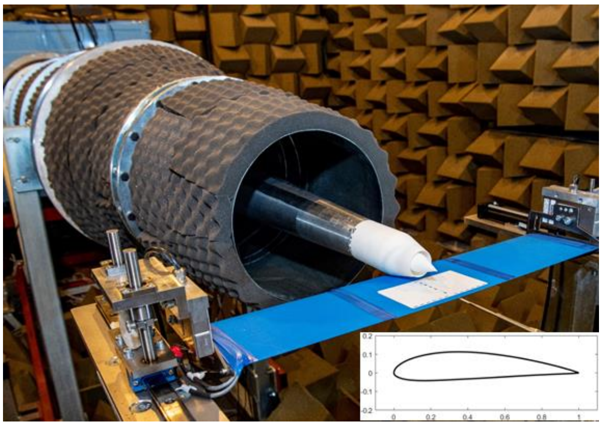


Figure 15: The baseline annular nozzle installed above the NACA4415 aerofoil on SOTON’s Doak Laboratory Flight Jet Rig

The novel geometries included: two elliptical, one triangular corrugated, and two offset bullet nozzles. In order to assess their effectiveness at reducing installed jet-flap interaction noise, they were each coupled closely to a uniform span NACA4415 aerofoil (Figure 15).

The streamwise vorticity introduced by the triangular corrugated nozzle was particularly effective at reducing the low-frequency installed jet-surface interaction noise (about 1dB). Significant reductions in correlation length were observed both along the span of the aerofoil TE and circumferentially in the near field of the isolated jet.

The second part of the task focussed on developing a method to predict the low-frequency far-field jet-surface interaction noise. SOTON’s DQ code is a mid-fidelity, semi-empirical method that uses either experimentally or numerically generated input data to describe the irrotational hydrodynamic source pressure field generated within the secondary-to-ambient shear layer of a subsonic, unheated jet. With the current version of the code, any influence of the primary-to-secondary jet shear layer (i.e., for a dual stream jet) is neglected and assumed not to significantly contribute to the overall source field – an assumption generally deemed to be reasonable for future Ultra-High-Bypass-Ratio (UHBR) engine-airframe architectures.

Status at project end: Various extensions were included in the DQ code such that more representative finite chord and cranked surface geometry effects could be computed. Furthermore, the model was successfully validated to predict in-flight co-annular jets, where the flight velocity is less than 100 m/s.

- *“Far-field pressure measurements of elliptic jets discharged close to a wing”, A. R. Proença (SOTON), 11th EASN Virtual International Conference on Innovation in Aviation & Space to the Satisfaction of the European Citizens / 2022 IOP Conf. Ser.: Mater. Sci. Eng., Paper No 012048, vol 1226, https://iopscience.iop.org/article/10.1088/1757-899X/1226/1/012048,* ***Gold Open Access***

Plasma actuators for jet-flap interaction noise control (TsAGI → Victor Kopiev)

The main idea of the control of the low-frequency installation noise is based on the assumption about the dominant role of instability waves in the process of noise generation. For each frequency, there is a linear transfer function between the near-field hydrodynamic pulsations of the jet, considered as if the plate is absent, and the far-field sound caused by the scattering of these pulsations on the trailing edge. It was also shown that the two first azimuthal modes mainly contribute to the low-frequency part of the installation noise. Therefore, if the control system is capable to reduce instability waves of low-order azimuthal modes, it should also lead to the reduction in installation noise.

In order to generate instability waves in the shear layer of turbulent installed jet, it is proposed to mount a high-frequency dielectric barrier discharge (HF DBD) actuator on the inner surface of the nozzle. Metal nozzles with special ceramic coating 1 mm thick were used. Discharge is created on the edges of the ring metal strip, and the nozzle itself serves as the second electrode. This configuration also allows the electrode to be mounted closer to the nozzle edge to increase the effectiveness of the instability wave generation.

Status at project end: Plasma actuators were released and the control strategy for artificial instability waves in presence of a wing was formulated and tested. It is shown that installation noise at the excitation frequency can be reduced or amplified depending on the phase shift between the acoustic excitation and plasma-based control action, provided the control action amplitude is properly adjusted in the free jet measurements. The effect of control is most pronounced at sideline and upstream directions of observation where installation noise dominates the acoustic signal radiated by the loudspeaker out of the nozzle.

- *“Plasma-based active closed-loop control of instability waves in unexcited turbulent jet. Part 2. Installed jet”, Oleg Bychkov (TSAGI), 25th AIAA/CEAS Aeroacoustics Conference 2019, 20.-24.05.2019, Delft, The Netherlands*

- *“Active control of jet-plate interaction noise for excited jets by plasma actuators”, Victor Kopiev (TSAGI), Journal of Sound and Vibration, Volume 484, 13 October 2020, 115515, https://doi.org/10.1016/j.jsv.2020.115515*

3.5. Boundary Layer Ingestion Effects

Boundary Layer Ingestion, or BLI, refers to an aero-propulsive configuration where a turbofan engine ingests part (or totality) of the boundary layer generated along an airplane, with an increase of the propulsion efficiency leading to a significant reduction in fuel consumption. Before ARTEM, most of the studies devoted to the BLI concept had focused on aerodynamic performances, and little had been achieved on the acoustic behavior of such engine implementation, which was the objective of a comprehensive ARTEM task.

BLI assumes that the air inlet is flush mounted on the aircraft surface, with the turbofan buried in the aircraft structure, connected to the air inlet by an S-duct. This implementation has several consequences on radiated fan noise. Compared to a classical nacelle installation, for which the fan ingests an axisymmetric mean flow (except for short and scarfed intakes) with very low turbulence intensity, the BLI configuration induces mean flow distortions and additional turbulence interacting with the fan, generating respectively tonal and broadband noise. On the other hand, long distance propagation through the S-duct should permit a significant sound attenuation, especially when using liners. Moreover, semi-buried engines may offer advantageous possibilities of noise shielding by the aircraft structure. The balance between these effects was not clear so far. Following subtasks have contributed to assess the potentiality of BLI on fan noise reduction, based on several configurations of ONERA's NOVA aircraft (Figure 1, left). NOVA is a "2035 skyline" concept with a classical tube-and-wing structure but using (i) a large lifting fuselage, (ii) a generic UHBR geared turbofan (BPR 16) for high fuel-efficiency, and (iii) integrating several promising innovative technologies. Its passenger capacity, range, cruise Mach number and altitude are similar to an Airbus A321-200.

Acoustic investigations have been conducted at low and high speed, first on the original NOVA-BLI configuration, with the engines buried at the rear side fuselage position, compared to the same NOVA aircraft with a more classic engine implementation based on nacelle pods at the rear side fuselage position (SFN, or side fuselage nacelle). Then, final activities focused on the more radical and promising NOVA-NAUTILUS configuration, with the engines installed at the extreme rear fuselage position to maximize the ingested boundary layer and minimize the azimuthal distortion of the fan inflow.

BLI full scale acoustic simulations (TUD → Damiano Casalino)

TUD used (i) the Lattice Boltzmann (LBM) commercial solver PowerFLOW (Dassault Systèmes) to compute the internal turbomachinery unsteady flow, including the blades/vanes unsteady loads and the local acoustic propagation up to control surfaces around the nacelles, and (ii) the associated FWH solver PowerACOUSTICS to derive the direct farfield noise radiated from these control surfaces, without acoustic installation effects.

Opposed to the initial planning, the details of the ONERA engine of the podded and the BLI aircraft (rotor and OGV designs, mass rates and flow regimes, nacelles internal/external aerolines) were considered as confidential, and could not be provided to the partner. Consequently, TUD selected a public NASA turbofan concept, named SDT (Source Diagnostic Test fan rig), and adapted this turbofan to fit the NOVA airframe in BLI configuration. For this purpose, TUD had to rescale the engine and design « from scratch » a S-duct guiding the flow from the intake to the fan of the SDT engine. Such design is tricky and requires many iterations that TUD could not afford. Consequently, their design generated excessive internal flow separations, resulting in excessive fan noise in the BLI configuration, up to 10-20 dB higher than for the isolated nacelle.

<u>Status at project end</u>: Using the Lattice-Boltzmann-based PowerFLOW code, TUD could demonstrate the calculation of noise generation for a BLI configuration. The results suggest a large noise penalty of the BLI concept, which is to a certain extent owed to the non-optimized design of the propulsion system. Given the availability of an optimized design, a certain noise increase might

be still present due to the inflow distortion. However, the applied method should be able to accurately predict the acoustic characteristics of the BLI propulsion system.

- *"Fan Noise Boundary-Layer Ingestion Installation Effects for NOVA Aircraft Configuration", G. Romani, 25th AIAA/CEAS Aeroacoustics Conference 2019, 20.-24.05.2019, Delft/ The Netherlands* **Green OA:** https://repository.tudelft.nl/islandora/object/uuid%3A7431c316-1511-4d8f-95e7-20a392e310fe?collection=research
- *"Numerical Analysis of Fan Noise for the NOVA Boundary-Layer Ingestion Configuration", Gianluca Romani (TU Delft), Aerospace Science and Technology 96 (2020) 105532, https://doi.org/10.1016/j.ast.2019.105532*, **Gold Open Access**

BLI aero-acoustic assessment (ONERA → Eric Manoha)

ONERA used (i) the *elsA* Navier-Stokes solver in unsteady RANS mode, either with a chorochronic periodicity for the isolated engine, or a full 360° computation for the BLI engines, to compute the blades/vanes unsteady loads, then (ii) the in-duct FWH acoustic propagation solver *FanNoise*, to derive the acoustic sound pressure and sound power level at the intake and nozzle. ONERA also used a boundary element (BEM) solver, *BEMUSE*, to account for acoustic installation effects by the airframe, with the acoustic incident field on the airframe computed with a FWH or Kirchhoff solver. In an intermediate step, ONERA also used its CAA solver *sAbrinA* to compute the local acoustic propagation of the generated duct modes (calibrated from the *FanNoise* computation) through the non-uniform mean flow, up to control surfaces around the nacelle.

The significant noise increase due to inflow distortions as predicted by the TU Delft computations was confirmed later by ONERA via computations of the internal acoustic SPL/PWL with *FanNoise*, achieved from the blade/vanes loads computed with PowerFLOW and provided by TUD: the levels in the BLI configurations were found about 12 dB above the isolated nacelle.

For the sound radiation, including the scattering by the airframe, ONERA showed that the BLI aircraft was only 5 to 6 dB noisier than the classic aircraft with podded engines, demonstrating that the partial shielding effects from the airframe could significantly attenuate the excess fan noise resulting from the BLI implementation.

The third activity achieved by ONERA was to compare the NOVA-BLI configuration and the isolated nacelle equipped with the original ONERA's turbofan engine especially designed for the NOVA family and in cruise flight (high speed) configuration. This approach led to reasonable deltas of about 5-6 dB between the fan noise generated by the BLI and classic engine implementations, showing the critical importance of the S-duct design to mitigate the inflow distortion.

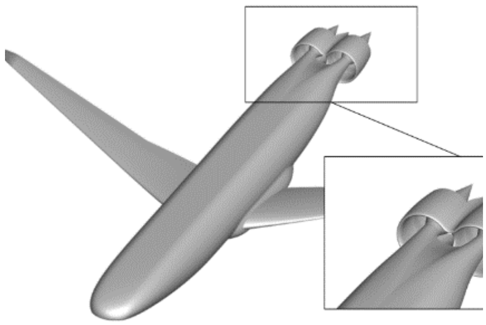


Figure 16: ONERAs NOVA NAUTILUS configuration

The final investigation by ONERA was an acoustic comparison of the isolated engine configuration (SFN) and the NAUTILUS configurations at low speed (take-off), using the same tools as before. This approach showed very limited excess noise for the NAUTILUS compared to the SFN, about +0.2 dB in the inlet and +2.2 dB in the nozzle, partly due to the limited azimuthal distortion of the twin fans inflow in the NAUTILUS implementation. This near-field solution was again used to compute the far field noise (but only at BPF and 2BPF) including acoustic installation effects generated by the airframe. This final realistic simulation showed that, at take-off for these first harmonics of BPF, the NAUTILUS configuration radiates more noise (by about 12 to 14 dB) than the SFN, mainly in the ground direction, a rather disappointing result attributed to (i) unfavorable behavior of actual duct modes propagation/radiation from the inlet (not captured by the *FanNoise* assumptions) (ii) much less scattering/shielding effects for the NAUTILUS with the engines isolated at the extreme rear end of the aircraft.

Status at project end: The combination of different tools proved to be well-suited to predict the noise generation of different BLI configurations. It has to be admitted, that both BLI configurations investigated are expected to generate additional noise. Great care is needed in the design of the inlet S-duct in order to reduce flow inhomogeneities and apply noise reduction devices (liners) where possible. Further, the actual placement of the engines need to be optimized with respect to both, aerodynamic efficiency considerations as well as noise radiation and shielding consideration.

- *"Acoustic Assessment of BLI Effects on Airbus NAUTILUS Engine Integration Concept - Part I: Noise Generation", M.Daroukh (ONERA), 28th AIAA/CEAS Aeroacoustics Conference. 14 June 2022 - 17 June 2022. Southampton,* https://doi.org/10.2514/6.2022-2943

- *"Acoustic Assessment of BLI Effects on Airbus NAUTILUS Engine Integration Concept - Part II: Noise Radiation", Mathieu Lorteau (ONERA), 28th AIAA/CEAS Aeroacoustics Conference. 14 June 2022 - 17 June 2022. Southampton,* https://doi.org/10.2514/6.2022-2992

BLI low-order modelling (ECL → Michel Roger)

ECL developed an analytical model of the inlet velocity distortion effects on inflow/fan and fan/OGV interactions, and the associated generated acoustic modes and in-duct propagation. A minimal amount of information is necessary as input: inlet velocity map, basic geometry of the duct and blades/vanes (all data that were provided by ONERA from the NAUTILUS unsteady flow computations). The model nonetheless accounts for arbitrary sweep and chord variations, which makes it attractive for the investigation of technological and design effects. The analytical formalism is implemented in a MATLAB environment. Its fast computational time is compatible with optimization algorithms.

Typical features of the inflow distortion simulated by ONERA are used as input for the model predictions of blade/vane interaction noise. Distortion effects on the tonal noise of a turbofan engine's fan stage, including rotor noise and stator noise interaction modifications are taken into account. In particular, it is shown that low-order cut-on azimuthal modes are regenerated at the blade passing frequency (which would be totally cut-off in a distortion-free configuration), with amplitudes up to 15dB below the amplitude of the cut-on modes at twice the blade-passing frequency, following the classical Tyler & Sofrin's rule.

Status at project end: Though some difficulties remain with the multiple-scale analysis when working with the NAUTILUS geometry, for which some modes exhibit a transition too close to the sources, the chained source and propagation models are considered as attractive tools for preliminary design. They can also help to interpret the results of numerical simulations.

3.6. Landing Gear Installation Effects

Landing gear (LG) noise is one of the major sources of noise in certification approach condition of modern civil aircraft, especially for long range aircraft where its contribution to total aircraft noise exceeds one-third. Numerous installation effects may potentially modify the isolated landing gear noise, either increasing (reflection under the wing, interaction of the landing gear wakes with the deployed flaps) or decreasing (wing circulation reducing the airflow speed). Today, prediction of landing gear noise remains a very complex task, both for the isolated and installed configurations. In this context, this task has addressed and improved our ability to design low-noise landing gear using favourable acoustic installation effects, a key for future aircraft developments.

Airbus/AI-F → Aline Scotto, SOTON → David Angland, DLR → Michael Pott-Polenske

This task was led by **Airbus**, who coordinated the identification and ranking of the main drivers of the main landing gear (MLG) installation effects for a wing mounted LG with and without close coupling with a belly fairing. During a dedicated workshop the partners proposed and down-selected the passive noise reduction technologies that would be investigated in the second part of the task. Airbus focused then the efforts on the design and manufacturing of several concepts that could enable the local flow deceleration and then reduce LG noise (e.g. low noise leg door concepts, droplet fairing). The analyses, shared with the partners, were based on small scale WTT data that were transposed to full-scale and on reference approach trajectory. Airbus finally delivered the noise attenuations of the most efficient technologies tested, at full scale and on reference approach trajectories, which could be directly used by WP3 partners for the assessments at A/C level in T3.1 and T3.2.

DLR contributed to the identification of installation noise drivers from experimental wind tunnel data analysis at model scale. For this purpose, DLR provided a 3-components high lifted wing model, allowing different slats and flap deflections, on which the AFLONEXT LG model could be directly installed. DLR conducted two Wind Tunnel Test campaigns in Acoustic Windtunnel Braunschweig (AWB) silent/anechoic open jet wind tunnel, providing an extensive experimental database including experimental data processing, corrections from wind tunnel effects and delivery to partners. Finally, DLR proposed and focused their effort on the design and manufacturing of a porous flap leading edge noise reduction technology, proposing 3 different samples integrated into a different flap, that were tested in the second wind tunnel test campaign. They carried out a comprehensive analysis of the noise reduction technologies WTT campaign at model scale, which was shared with partners.

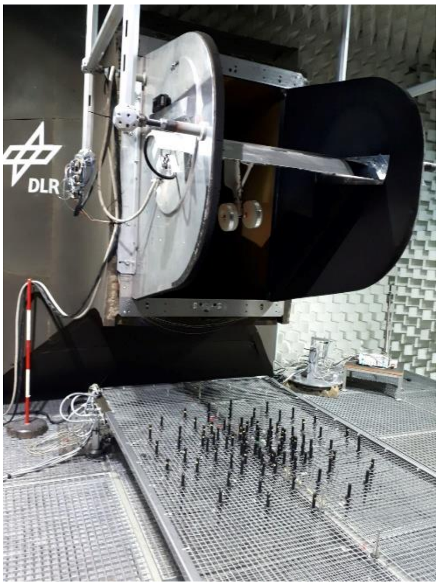


Figure 17: Landing gear model in AWB wind tunnel

SOTON contributed also in the identification and ranking of LG installation noise drivers, through numerical simulations with Lattice Boltzmann (ProLB solver) and CAA simulations on 3 configurations: isolated high lifted wing, isolated landing gear and high lifted wing with installed landing gear. A validation against experiments was performed. SOTON proposed then some LG installation noise reduction technologies based on the LG wake turbulence control through downstream mesh fairings: they did the design and manufacturing of numerous proofs of concepts and one installed fairing on the LG model. They conducted a wind tunnel test campaign in SOTON

AWT (Anechoic Wind Tunnel), whose objective was to down-select the most promising technologies on isolated LG for the second entry in AWB for LG installed under high lifted wing. Their activity included experimental data processing, corrections from wind tunnel effects and delivery to partners. SOTON finally worked on the elaboration of a simple model to address the noise generation mechanism due to landing gear wake / flap interaction.

Status at project end: Extensive experimental database acquisition in AWB and SOTON acoustic wind tunnel on reference high lifted wing and LG installed: aerodynamics measurements and acoustics measurements performed including the effect of slat/flap deflection on LG noise including several design proposals for noise reduction means. First computations with ProLB solver of LG installed under high lifted wing configuration were achieved. The results of simulations of installed LG showed in general good agreement with experimental data with some deviation for unsteady surface pressure on upper and lower side of the flap. Qualitatively, trends were well captured.
The importance of noise sources in installed configuration could be addressed and ranked: (from greatest to the least):

- Local velocity impinging the landing gear:
- Landing gear wake / flap interaction:
- Acoustic phenomena: reflection, diffraction and refraction

Based on the extensive activities, a landing gear wake flap interaction noise model was developed and validated against the ARTEM experimental data and the rod-airfoil benchmark case.

Future work: Physical LG models and noise reduction solutions will used for future projects (e.g. H2020 project INVENTOR, French project CORAC and UK funded project LANDOne). The experimental and numerical data base as well as implemented models and simulation approaches will support further improvement of low-noise landing gear design and assessment of reduction means.

- *“The Use of Porous Meshes to Reduce Landing Gear Wake - Flap Interaction Noise, F. Lara (SOTON), 28th AIAA/CEAS Aeroacoustics Conference. 14 June 2022 - 17 June 2022. Southampton, https://doi.org/10.2514/6.2022-3044*

3.7. Distributed Propulsion Systems

The global objective of the research work in this task was the investigation and mitigation of the noise emission of Distributed Electric Propulsion (DEP) systems. More compact and more powerful electric motors are offering interesting perspectives for the development of disruptive and versatile air transport concepts for short-term general aviation, and mid-term conventional and new commercial aircraft architectures.

Thanks to new degrees of freedom offered by electrical propulsion, many distributed engine integration solutions can be considered. Among them, two configurations have been investigated in this task due to their near-term exploitation potential on large Remotely Piloted Aircraft systems (RPAS) and CS-23 category aircraft. The first one is a tractor configuration, where the propellers are upstream to the wing leading-edge. One asset of that system is to provide a dynamic pressure over the wing that is substantially larger than made possible by the flight speed alone. This enables relatively low takeoff and approach distances, and a more efficient wing design tailored for cruise conditions with smaller chord and reduced drag. The second configuration features pusher propellers in the above-aft part of the wing, mounted on overwing pods. Being installed on the wing suction side, it may improve again the lift thanks to flow acceleration (Figure 18). It is of fundamental importance to select baseline installation concepts that are aerodynamically efficient to guarantee that the research on noise reduction methods has a strong exploitation potential beyond this research project.

Figure 18: Wind tunnel model for DEP investigations: wing with 3 propellers mountable in pusher or tractor configuration

PVS → Jernej Drofelnik, INCAS → Corneliu Stoica, ONERA → Antoine Hajczak,

VKI → Julien Christophe

This task was led by **Pipistrel Vertical Solutions** (PVS). PVS was mainly responsible of the design and manufacture of the modular DEP model which included a constant chord wing airfoil and 3 propellers, in either pusher or tractor mode, with all necessary power supply and rotation controls devices. The design of the model, and especially the choice of the propellers, relied on numerical simulations achieved with the NUMECA solver.

Aerodynamic and acoustic experiments with this modular DEP model were achieved by **INCAS** and PVS in INCAS' closed section wind tunnel, to evaluate the influence of several parameters, including the axial/vertical position of propellers with respect to the wing and the relative rotation direction (co or contra) of close propellers. Aerodynamic efforts were measured with a specific set-up using a podded balance, whereas acoustic measurements were achieved with a microphone array with the 2D wing attached to the lateral walls.

In parallel of these experimental activities, **ONERA** and **VKI** achieved numerical simulations of the tested configurations with the dual purpose of confirming the experimental outcomes and validating their solvers.

VKI and ONERA worked on the development of the simulation chains to compute the noise radiated in DEP configurations. They proposed different methodologies to compute the tonal and broadband noise and compared the numerical predictions with the wind tunnel data.

One of the main challenges encountered was to compare numerical results with experimental measurements performed in a non-anechoic environment, which required to include the wind tunnel effects in the numerical methods. The simulation methods showed a fair agreement with the wind tunnel acoustic spectra.
In the final stage of the project, the focus was on finding parameters for noise reduction of DEP system through experimental and numerical parametric studies.

Three noise mechanisms were investigated: the prediction of tonal self-noise emitted by the propeller(s), the prediction of trailing-edge broadband self-noise, due to the scattering of both suction and pressure side boundary-layers at the trailing edge, and prediction of tonal wake interaction noise, which is due to the interaction of the propeller viscous wake with the main wing in tractor configurations. Parametric investigations that were done included the variation of the propeller position relative to the main wing for a single propeller, variation of the clocking angle between two propellers to analyze its effect on the radiated tonal noise. They showed that synchronization can yield beneficial noise reductions at very specific angles while globally increasing the noise levels everywhere else. A tradeoff must therefore be sought depending if noise reductions are desired at very specific angles or in a more global manner.

Status at project end: Aero-acoustically optimized DEP configuration would include a combination of the noise shielding effect by the DEP wing and optimized relative blade phase angle between the multiple propellers. Data suggests that due to a smaller noise footprint of pusher propeller in comparison with the single tractor propeller configuration, and due to slightly better aerodynamic characteristics, the pusher propeller configuration is more optimal than the tractor configuration.

Future Work: In future projects, it would be advised to run additional wind tunnel test campaign in an anechoic wind tunnel, to avoid the multiple reflections on the wind tunnel walls. This would allow further validation of the numerical methods developed within this project, avoiding the need to include the wind tunnel effects in the numerical methods. An experimental campaign should use the improved DEP mock-up which would allow to control the relative blade phase angle between the propellers and would enable to test more geometric positions.

- *"Measurement and modelling of aero-acoustic installation effects in tractor and pusher propeller architectures", Jernej Drofelnik (PPS), 27th AIAA/CEAS Aeroacoustics Conference (part of AVIATION 2021), 2.-6.August 2021,* https://doi.org/10.2514/6.2021-2301

- *"Numerical Parametric Investigation of Aeroacoustic Installation Effects in a Distributed Electric Propulsion System", Antoine Hajczak (ONERA), AIAA 2022-3006, 28th AIAA/CEAS Aeroacoustics 2022 Conference, June 14-17, 2022, Southampton, UK,* https://doi.org/10.2514/6.2022-3006

3.8. Configuration Analysis “2050”

In order to achieve a step-change in fuel consumption and emission reduction (gaseous emissions and noise), changing the general layout and structure of the aircraft might be required. In several studies it is anticipated, that blended wing aircraft might be the most promising solution to achieve that step change. Although it would probably require a complete restructuring of the current airport aircraft handling, the lift-providing, low drag body would reduce fuel consumption while an overwing installation of the propulsion system provides extensive shielding of generated noise towards observers at the ground.

Conceptual design of two blended wing body aircraft (U Roma3 → Umberto Iemma)

In ARTEM a conceptual design of two such aircraft was performed using the U Roma3 developed tool FRIDA in order to quantify the expected noise benefit and investigate appropriate means for additional noise reduction which are in some cases quite different from conventional tube&wing aircraft.
BOLT – a Blended wing body with Optimized Low-noise Technologies - considered the best candidate, within skyline 2050, for long range commercial routes using conventional UHBR engines (BPR>16). The conceptual optimization is based on a typical long haul mission profile.
In parallel, a design of a REBEL – a REgional Blended-wing-body ELectric-propelled – was considered as disruptive concept, devoted to short and medium range commercial routes. In particular, the analysis of this new concept addressed several parameters as: the hybrid-partially electric propulsion system, the size and the number of the propellers needed and the related distribution along the aircraft (REBEL-HEP). This kind of vehicle represents a different version of the “classical” Blended-Wing-Body (BWB) due the specific properties of the propulsion system. The baseline configurations equipped with conventional technologies and engines (REBEL-C) was also analysed in terms of performance and noise based on low order models.

REBEL should carry 100 passengers on a range of 900 nm, the BOLT is a long haul concept sized for a 400 passengers payload.

		BOLT	REBEL
Range	*nmi*	5500	900
Payload	*#pax*	400	100
Cruise altitude	*ft*	43000	25000
Cruise Mach number	-	0,84	0,50

The initial analysis was performed by UROMA3 using the in-house tool FRIDA (Framework for Innovative Design in Aeronautics), capable of multi-objective, multidisciplinary optimization of design and operations of innovative concepts under environmental constraints.

Optimisation routines have been performed in order to obtain optimised layouts for BOLT, REBEL-C and REBEL-HEP: objectives are related to aircraft performances (glide ratio and weight), whereas the constraints pertain both geometrical characteristics and aerodynamics.
It has been noted that a unique compromise solution for both REBEL configuration could be picked, as the approximated Pareto frontiers, in the design space, turn out to be close to each other.

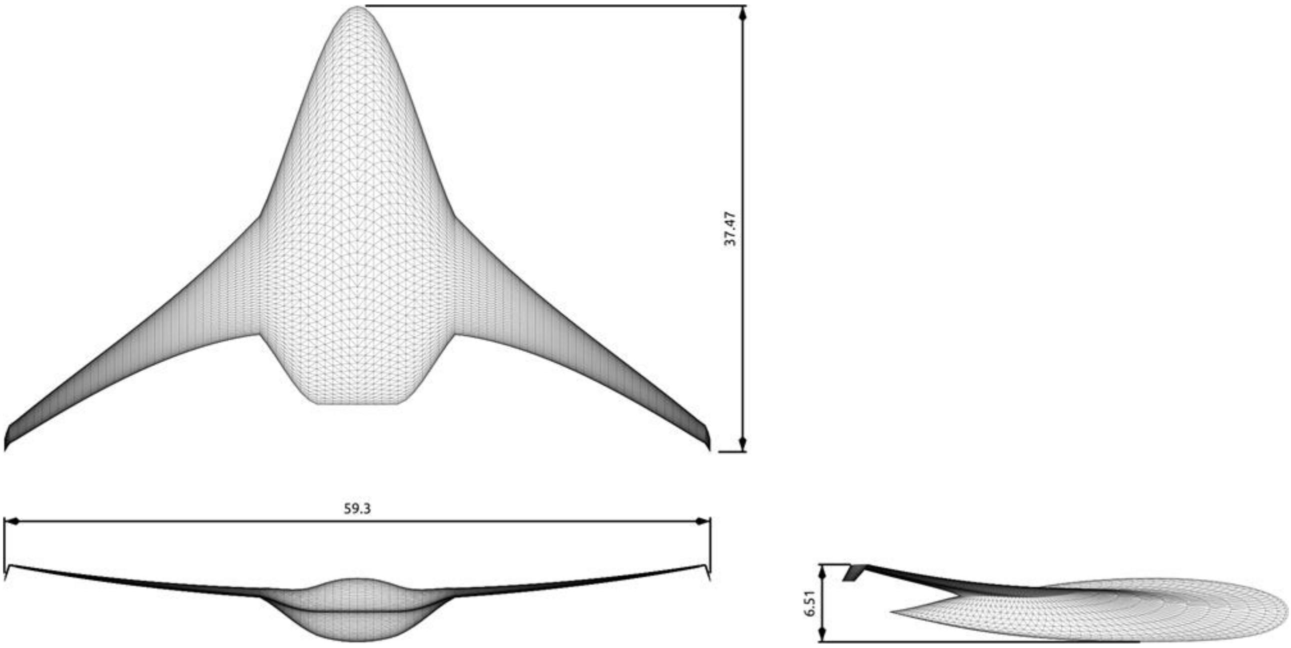


Figure 19: BOLT - optimized layout and main performance characteristics (©UNIROMA3, 2018)

Stall speed	**Take-off**	*m/s*	73,1
	Mid-cruise	*m/s*	152,3
	Landing	*m/s*	55,8
Average cruise efficiency		-	21,8
Mid-cruise wing load		*kg/m²*	306
Mid-cruise thrust to weight ratio			0,046

In further iterations, the design was refined, the required thrust requirements for take-off, cruise and landing estimated and an analysis for the optimal placement of the propulsion system was performed. In addition, the distributed propulsion system of REBEL-HEP has been devised in cooperation with CIRA.

A model of the REBEL-H has been implemented in the free flight simulation environment JSBSim thanks to the work of Marco Stefanini, MSc student in Aeronautical Engineering at Roma Tre. The response of the aircraft to the pilot's inputs is calculated using FRIDA.

➔ https://www.youtube.com/watch?v=zS3Fz8guVQ8

Status at project end: The conceptual design of two blended wing body aircraft was successfully achieved. The BOLT configuration was also used in the parallel running H2020 project ARTEM for noise assessment of future aircraft fleets. During the project, certain improvements to the MDO design tool FRIDA could be made. It proved difficult, to predict with certain accuracy the noise characteristics of future UHBR engines with BPR>12 due to the missing data on engine detailed design, and respective weighting of noise sources.

- *Centracchio, F., Rossetti, M. and Iemma, U., "Approach to the Weight Estimation in the Conceptual Design of Hybrid-Electric-Powered Unconventional Regional Aircraft" Hindawi, Journal of Advanced Transportation, Volume 2018, Article ID 6320197, https://doi.org/10.1155/2018/6320197*

- *Numerical characterisation of the aeroacoustic signature of propellers array for distributed electric propulsion, Giovanni Bernardini (U Roma3), Special Issue "Airframe Noise and Airframe/Propulsion Integration" of Applied Science (MDPI),* ***Gold Open Access***

BENCHMARK ACTIVITIES
ONERA → Ingrid LeGriffon, DLR → Lothar Bertsch, CIRA → Francesco Adamo

Before applying noise prediction tools to new designed configurations, a benchmark among three noise predictions tools: AGNES (CIRA), PANAM (DLR), and CARMEN (ONERA) was made.

Five distinctive noise sources were considered: jet, fan inlet, fan outlet, main landing gear and nose landing gear. Their positions on the aircraft were chosen with the help of URoma3 and based on geometric assumptions of the engines. In order to keep results comparable between partners, it was decided to use single radiating monopoles at the source location. Despite general similarities in the tools and the results of the prediction, the benchmark also revealed some differences in particular in the assessment of shielding efficiency. This underlines the necessity of further cooperation and mutual work to assess and increase reliability of those predictions which are needed for the early design phase of new aircraft systems.

In a further activity, the tools of DLR and ONERA were used to predict the expected noise reduction for the BOLT configuration when increasing the engine bypass ratio or applying specific low-noise technologies (Figure 20). Despite the differences (due to the different shielding prediction), the trends are well captured by both tools, demonstrating that with the specific characteristics of the overwing installation of the engine the increase in bypass ratio (BPR) does yield only small additional noise reduction on overall aircraft noise.

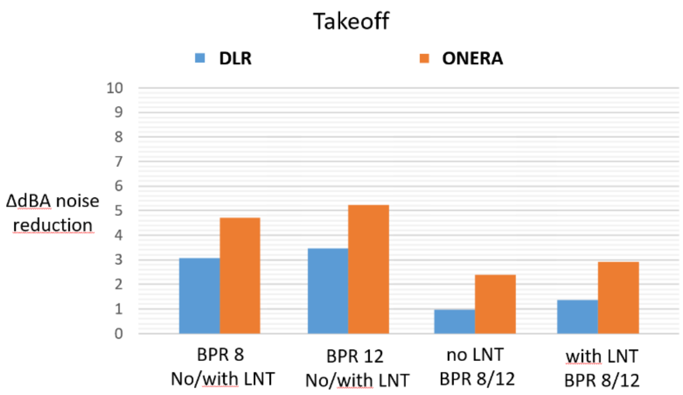


Figure 20: $L_{A,max}$ noise reduction between aircraft with and without LNT package (two to the left), and BPR8 and BPR12 configurations (two to the right) for takeoff configurations

In addition to doing a noise impact evaluation on the ground, DLR and ONERA transferred noise emission data at aircraft level to EMPA for auralization and psycho-acoustic laboratory tests.

Status at project end: Noise predictions for novel aircraft configurations have been successfully achieved for certification points and along given trajectories thereby being able to provide inputs for aircraft fleet predictions and auralization.

Future work: Improved models for noise sources and shielding should lead to a reduction of prediction uncertainties and will be in the focus of future activities

- *"Flyover noise evaluation of low-noise technologies applied to a blended wing body aircraft", Ingrid LeGriffon (ONERA), Internoise 2022, Glasgow/UK, 21.-24.8.2022*

Aerodynamic and acoustic calculations for "2050 aircraft" configurations incl. DEP, single aircraft and fleet assessment for airport (CIRA → Francesco Adamo)

In a close cooperation with the activites of U Roma3, CIRA investigated the distributed propulsion system for the REBEL-HEP and the implications of different spacing and phasing of the respective rotors.
In further activities, the noise predictions for the BOLT and REBEL aircraft in operation were made with and without low noise technologies applied and compared with a standard aircraft.
Napoli-Capodichino (ICAO code: LIRN) was selected as an example for detailed noise predictions for single aircraft movements and fleet assessment, provided that it is also considered in the ongoing Italian project PROSIB (Propulsion and Hybrid Systems for Aircraft and Rotorcraft), as target operational airports for hybrid vehicles with less than 100 passengers on-board, which are comparable to the REBEL-HEP configuration.
This noise reduction is confirmed by Figure 21 where the noise contour surfaces expressed in geo-localized L_{AE} are shown for a conventional aircraft (upper part of the Figure) and for the BOLT aircraft. Observing the graphic representation, we can appreciate that the contours extension and the invested territorial areas by BOLT are substantially smaller than for the corresponding standard aircraft. The same indications were derived for REBEL simulations.

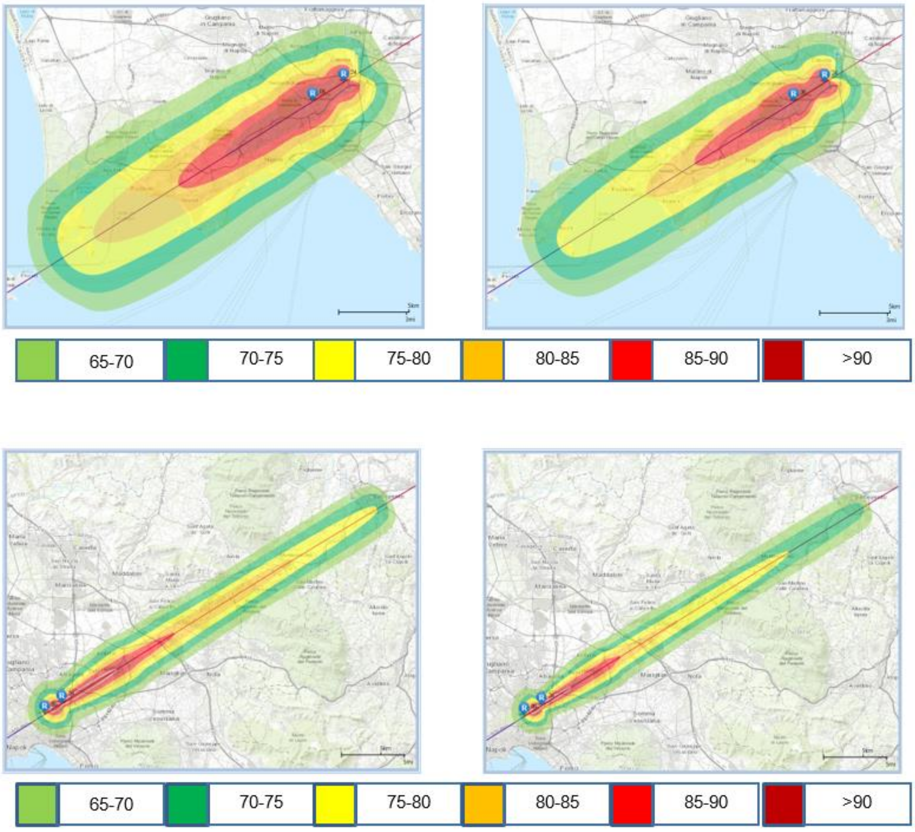


Figure 21: Graphical representation of equal loudness contours for Standard (left) and BOLT (right) configuration in terms of L_{AE} (dBA) for a standard runway 24 takeoff (upper part of the figure) and landing (lower part).

Status at project end: Detailed predictions of novel aircraft configurations could be achieved. The prediction process revealed the necessity for some tool adaptations when considering conceptual aircraft designs, where only limited data is available for many of the expected noise sources.

Future work: The comprehensive results of this study shall be published in a dedicated article during the next months.

3.9. Configuration Analysis “2030”

Airbus → Jie Liu, RRD → Christoph Richter, SAE → Guillaume Bodard, DASSAV → Stephane Lemaire

The objective of this task was to assess the potential technical impact of implementing Low Noise Technologies (LNT) into a wide range of products, from business jet to long-range (LR) and small-medium-rang (SMR) advanced aircraft (Entry Into Service 2025-2030).

After reviews with project partners, the most relevant ARTEM technologies applicable to business jet, LR, and SMR mid-term advanced 2025-2030 aircraft platforms are summarized on the Table 1. Other technologies have not been proposed either because they were not suitable for these platforms or because no significant noise benefit has been demonstrated at technology level. Due to low TRL or time constraints, technology integration impacts on aircraft design (such as weight, drag …) have not been provided. Only purely acoustic impacts have been studied and assessed.

<table>
<tr><th>WP</th><th>Task</th><th>Technology</th><th>LR</th><th>SMR</th><th>Business Jet</th></tr>
<tr><td rowspan="4">1</td><td rowspan="3">1.1 Absorption technologies for 2035</td><td>Multiple folded cavity core liner</td><td>x</td><td></td><td>x</td></tr>
<tr><td>Slanted septum core liner</td><td>x</td><td></td><td>x</td></tr>
<tr><td>Zero Mass Flow liner</td><td>x</td><td></td><td></td></tr>
<tr><td>1.3 Shielding</td><td>Effects of the viscous mean flow on shielding of fan noise by the main wing of a Falcon jet</td><td></td><td></td><td>x</td></tr>
<tr><td rowspan="5">2</td><td rowspan="3">2.1 High lift devices</td><td>Kruger slat</td><td>x</td><td>x</td><td></td></tr>
<tr><td>Very long chord slat</td><td>x</td><td>x</td><td></td></tr>
<tr><td>Adaptive slat gap</td><td>x</td><td>x</td><td></td></tr>
<tr><td rowspan="2">2.4 LG installation noise</td><td>Beneficial wing aerodynamic design</td><td>x</td><td>x</td><td></td></tr>
<tr><td>Porous flap leading edge device</td><td></td><td>x</td><td></td></tr>
</table>

Table 1: Technology package definition for business jet, LR and SMR mid-term advanced 2025-2030 aircraft platforms

Main characteristics of business jet, LR and SMR mid-term advanced aircraft platforms are presented on Table 2:

Design characteristics	SMR	LR	Business Jet
Pax number (Design mission)	~ 250	~ 330	~ 12
Design range (nm) @ (Standard Passenger Payload)	3000nm	7000nm	6200nm
Cruise Mach number	0.78	0.85	0.88

Table 2: Business jet, LR and SMR aircraft platform design characteristics

- LR: CleanSky2 type platform, fitted with two BPF15 turbofan engines under wing installation and wing landing gear.
- SMR: defined for ARTEM fitted with two BPF 11 turbofan engines under wing installation and wing landing gear.
- Business jet: CleanSky2 type platform, fitted with three BPR5 turbofan engines installed on the rear fuselage, above the wing.

Airbus and Dassault Aviation used their in-house static-to-flight transposition tools ROOTS (Airbus) and ANIS (Dassault) for noise impact of ARTEM low noise technologies (LNT) in certification conditions and in operational conditions assessment.

Certification noise is computed on trajectories and microphones consistent with the standard described in ICAO Annex 16. Effective Perceived Noise Level (EPNL) is computed for reference aircraft and LNT aircraft. Noise impact is expresed in ΔEPNL between LNT and reference aircraft (ΔEPNL = Optimized configuration – Baseline configuration).

The noise benefits of ARTEM technologies for total aircraft at three certification points and operational conditions are presented on Table 3 and Table 4 for the commercial aircraft platforms.

Total A/C - ΔEPNL (EPNdB) = EPNL Conf. ARTEM – EPNL Conf. Baseline		
Platform	**SMR**	**LR**
Approach	-0.6	-0.7
Flyover	-	-0.3
Lateral	-	-0.5
Cumulative	**-0.6**	**-1.5**

Table 3: EPNL benefit of technology combinations for LR and SMR

SEL (dBA) iso-contour	**Baseline footprint (km²)**			**Footprint reduction with technology (%)**		
	SMR APP	LR APP	LR TO	SMR APP	LR APP	LR TO
75	20.7	29.8	19.7	-11.8	-7.4	-5.4
80	5.8	12.3	5.4	-40.7	-13.4	-7.1
85	0.7	2.1	2.4	-13.5	-18.3	-10.9

Table 4: Footprint comparison between conf. with technologies combination and their respective baseline for LR and SMR

The combination of the most promising ARTEM technologies bring up to 1.5EPNdB reduction on cumulative certification noise levels for LR (approach and take-off), and 0.6EPNdB for SMR (only approach) which may be a bit optimistic regarding the fact that integration effects (on drag, weight etc.) of the ARTEM technologies have not been addressed in ARTEM assessment.

Status at project end: The process of implementing low TRL technologies into full aircraft assessment was successfully achieved thanks to the support of industrial partners using their capabilities of upscaling of results and existing prediction tool chains. The noise reduction technologies considered in ARTEM have a significant potential to be applied already for near-term aircraft configurations with a large potential specifically for certain liner structures, high-lift-devive design modifications, and landing gear reduction means.

Future work: In order to mature promising low noise technology concepts, specific research and development activities with respective funding are needed on national and European level.

3.10. Auralization

EMPA → Reto Pieren, partly supported by U Cergy → Catherine Lavandier

Within this task, flyovers of future aircraft configurations were auralized and used in laboratory listening experiments to evaluate their noise impact on humans.
Prior to assessing future aircraft configurations, a systematic and rigorous hierarchical validation of auralizations of current today's jet aircraft (Airbus A320-214 and A340-313) by means of comparisons with field recordings was conducted.
The recordings were taken from a previous field measurement campaign around Zurich airport, Switzerland, from microphones located close to the noise certification points. From the campaign, also meteorological and flight data recorder (FDR) data was available, yielding the necessary input data (e.g., flaps setting, low compressor speed N1, flight trajectory etc.) for the simulations and thus auralizations of the measured reference flights. The auralized data agree very well with field recordings, with a mean difference between syntheses and recordings of –0.9 dB (standard deviation ±1.5 dB) in the A-weighted sound exposure level.

In addition to comparing computed noise indicators, a psychoacoustic validation was done in dedicated laboratory listening experiments to assess the quality of the auralizations regarding the identifiability of synthesized sounds, their plausibility, and their effects on humans (here, annoyance). The auralizations' whole simulation chain was fully blind to the reference field measurements, computed with independent calculation models and without any tuning to the measurements. To consider the uncertainty in the source modelling, two simulations based on different input datasets provided by different tools and partners from ARTEM partners were used.

The psychoacoustic validation comprised three levels:

- Part I – Direct comparison of synthesized with recorded stimuli
- Part II – Ranking of auralizations and recordings regarding plausibility of the stimuli
- Part III – Subjective annoyance ratings to test whether auralizations and recordings differ with respect to noise effects

The experiments were conducted at EMPA's listening test facility AuraLab.

After successful completion of the validation study, auralizations of advanced aircraft configurations (blended wing body, BOLT) for the year 2050 with possible low-noise technologies (LNT) developed within ARTEM (again based on the two independent simulations) were compared to auralizations (also syntheses, using the same tools) of current aircraft of similar range and mission, namely, a long range tube-and-wing jet aircraft. For this study, a total of 36 syntheses were created using EMPA's auralization code AURAFONE.

Figure 22 compares level-time histories of psychoacoustic loudness for a departure of a current and the studied BOLT aircraft. Besides very different source directivities of the two aircraft, the BOLT aircraft is also substantially less loud throughout the whole flyover (maximum loudness reduction by a factor of about 4–6).

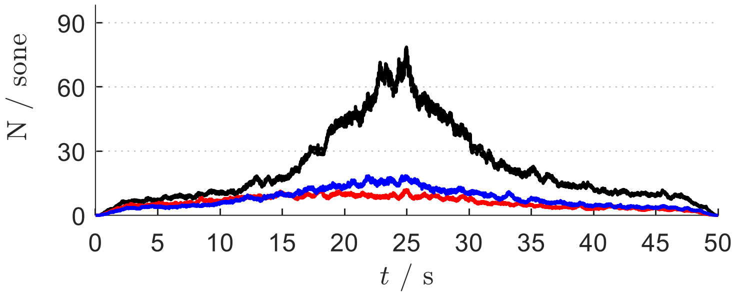


Figure 22: Time-histories of psychoacoustic loudness (N) of the departing current technology aircraft(black curve) and blended wing body aircraft BOLT (blue curve) with additional low-noise technologies (red curve BOLT with LNT) at 9 km distance from the brake release point.

Figure 23 shows the noise annoyance to different aircraft concepts (aggregated data: Reference aircraft (RefAC), and BOLT (AC50) without and with LNT). The listening experiment revealed that overall (i.e., arithmetic mean over all receiver positions, procedures, engines and simulations) the type of aircraft concept was strongly linked to annoyance. Annoyance was 3.0 units on the 11-point scale lower for the AC50 without LNT and even 3.6 units lower with LNT than the RefAC which indicates that both, the optimizations of the aircraft concept (BOLT) as well as the LNTs are effective measures to reduce annoyance.

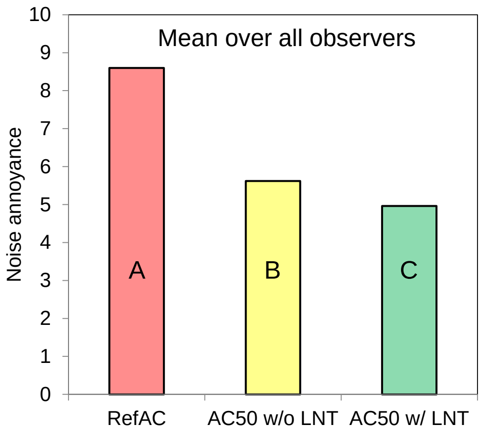


Figure 23: Main psychoacoustic experiment: Observed noise annoyance of the aircraft concepts (RefAC, and AC50 without and with LNT). Statistically significant differences ($p < 0.05$; pairwise comparisons with Bonferroni correction) are indicated by differing capital letters.

An auralisation demonstration video of BOLT with LNT is publicly available on YouTube: https://youtu.be/5cuORVT-Wt8.

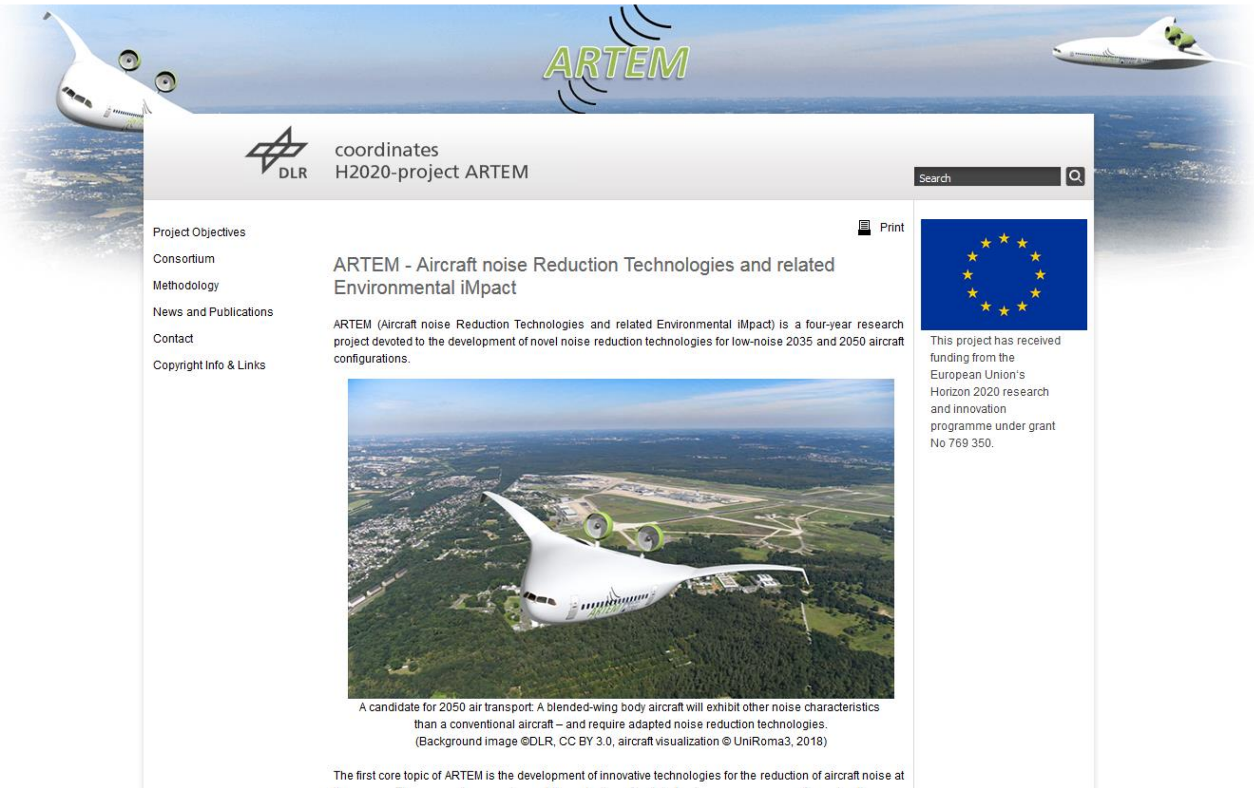
Status at project end: This activity demonstrated successfully the ability to auralize future aircraft concepts using established and validated tool chains. As input, good predictions of the different noise sources and their changing characteristics along the expected trajectories for take-off and approach are required. This task revealed that the BOLT configuration with LNT is substantially less noise annoying than current long-range tube-and-wing aircraft.

Future work: In ongoing projects LION (D-A-CH, 2020-2023), the modelling of atmospheric turbulence effects and aircraft noise annoyance are further investigated (project AVALON Swiss-funded FOEN, 2022-2023, with respect to drone operations) and project PACMAN (EMPA, 2022-2024) asseses in a meta-analysis several psychoacoustic experiments.

- *"A Comparison of Aircraft Flyover Auralizations by the Aircraft Noise Simulation Working Group", Reto Pieren (EMPA), 26th AIAA/CEAS Aeroacoustics Conference (part of AVIATION 2020), 15.-19.06.2020, Reno/USA*
- *"Auralization of aircraft flyovers with turbulence-induced coherence loss in ground effect", Reto Pieren (EMPA), Journal of the Acoustical Society of America (JASA), Volume 151, Issue 4, https://doi.org/10.1121/10.0010121* **Gold Open Access**

4. Online resources

The **ARTEM website** is accessible at**:** www.dlr.de/ARTEM



A project flyer and the publishable summaries are available for download at the ARTEM website.

- ARTEM at the EC information site (CORDIS):
  https://cordis.europa.eu/project/rcn/212367/en

- Project fiche of ARTEM at the INEA site:
  https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-transport/aviation/artem

LINKS:

- Coordination Action for European Noise Research within H2020 project ANIMA:
  https://anima-project.eu/what-does-anima-do/global-co-ordination/

- Future Sky initiative of EREA:
  http://www.futuresky.eu/projects/quiet-air-transport

5. The ARTEM Consortium

Advanced Engineering Design Solutions SARL (AEDS)

Airbus Operations SAS (Airbus)

Centro Italiano Ricerche Aerospaziali (Italian Aerospace Research Center CIRA)

Le Centre National de la Recherche Scientifique (CNRS)

COMOTI, Romanian Research & Development Institute for Gas Turbines

Dassault Aviation SA (DASSAV)

Deutsches Zentrum für Luft- und Raumfahrt (DLR), German Aerospace Center

Ecole Central de Lyon (ECL)

École Polytechnique Fédéral de Lausanne (EPFL)

Swiss Federal Laboratories for Material Science and Technology (EMPA)

National Institute for Aerospace Research Elie Carafoli (INCAS)

Stichting Nationaal Lucht- en Ruimtevaartlaboratorium (NLR), Netherlands Aerospace Centre

Office National D'Etudes et de Recherches Aerospatiales (ONERA), French Aerospace Lab

PIPISTREL VERTICAL SOLUTIONS d.o.o. (PVS)

Rolls-Royce Deutschland Ltd & Co KG (RRD)

Safran Aircraft Engines (SAE)

University of Southampton (home of the Airbus Noise Technology Centre and the Rolls-Royce University Technology Centre in Noise) (SOTON)

Central Aerohydrodynamic Institute (TsAGI)*

Technische Universität Braunschweig (TUBS)

Delft University of Technology (TUDelft)

University of Bristol (U Bristol)

Cergy Paris Université (UCP)

Universita' Degli Studi Roma Tre (URoma3)

The von Karman Institute for Fluid Dynamics (VKI)

** Due to the Russian aggression against Ukraine starting in February 2022, unfortunately, also the scientific cooperation within ARTEM with the Russian partner TSAGI had to be stopped in the final stage of project. TSAGI participated before on own budget and did not receive any funding from EC within ARTEM.*

6. Contact for further information

The project was coordinated by the German Aerospace Center (DLR), Dept. Engine Acoustics.

Inquiries should be directed to

Dr.-Ing. Karsten Knobloch
German Aerospace Center (DLR)
Institute of Propulsion Technology | Engine Acoustics
Mueller-Breslau-Str. 8 | 10623 Berlin | Germany

Mail to: artem@dlr.de

Project supervision at the European Commission:

Innovation and Networks Executive Agency (INEA)
Chaussée de Wavre 910
W910 03/60
B-1049 Brussels, Belgium

7. Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 769 350.

ARTEM and other projects within the MG1-2-2017 call "Reducing Aviation Noise" were initiated by the EREA "Future Sky" initiative.