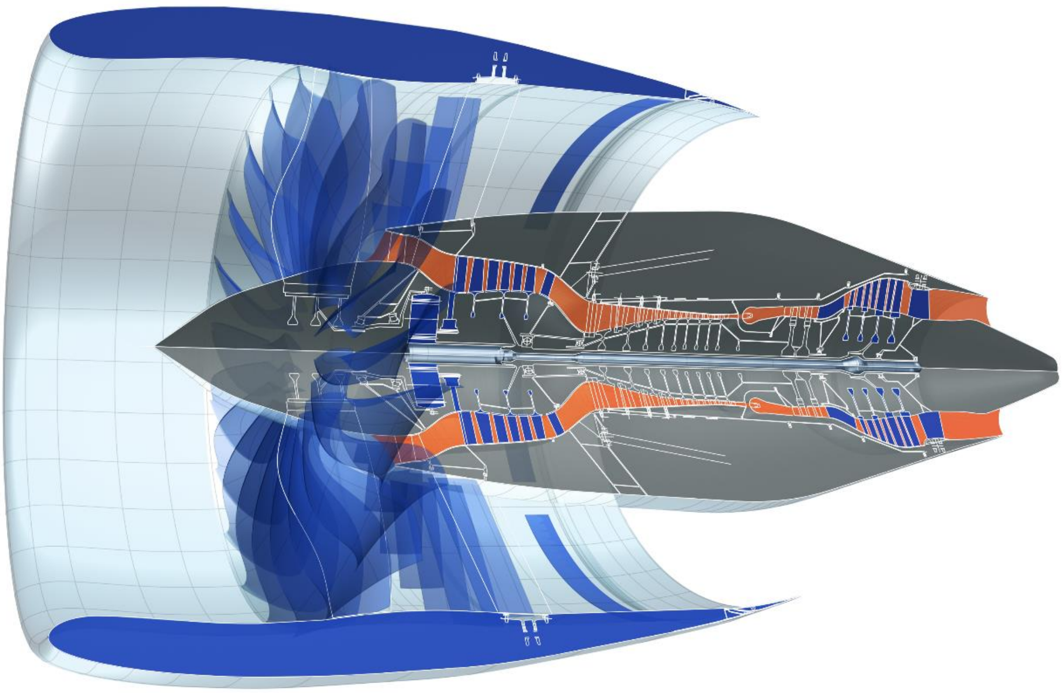
ENOVAL

Ultra High Bypass Ratio Aero Engines

Final Report



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Executive summary

A further reduction of aero engine emissions to contribute to a cleaner and quieter aviation future was the overall ambition and objective for the activities of 35 partners within the EU funded Level 2 aero engine project ENOVAL (ENgine mOdule VALidators).

Since its start in October 2013, this project has developed the next step of engine technologies to achieve or surpass the ACARE 2020 goals on the way towards Flightpath 2050 and it completes the European 7th Framework Programme (FP7) roadmap of Level 2 aero engine projects such as LEMCOTEC for core engine technologies and E-BREAK for system technologies to enable ultra-high OPR engines.

The ENOVAL project concentrated on geared ducted turbofan engines, which are considered the next generation of commercial aircraft applications with an entry into service date of 2025 onward. It developed technologies for the low pressure system to enable ultra-high by-pass ratio propulsion systems (12 < BPR < 20) with ultra-high overall pressure ratio (50 < OPR < 70).

Now at the end of this five-year project we are able to present the results of all our efforts in this final report and can conclude that we have achieved our intended objectives to validate innovative low pressure system technologies at component level up to TRL5, which will reduce the CO_2 emissions in terms of fuel burn up to -5% and engine noise -1.3 ENPdB. The potential application range of those technologies is extremely wide, representing approximately 90% of the commercial market.

These achieved ENOVAL results have significant environmental, economic and societal impacts. ENOVAL is tackling the challenge to continuously reduce aviation's environmental impact in the face of ever-increasing demand by laying the basis for new, more environmental products in aviation industry. By this, ENOVAL strengthens the competitiveness of the European engine industry and enables it to deliver the best products and services worldwide and helps to maintain Europe's leading position in aeronautics. ENOVAL fostered the collaboration of European academia, SMEs and industry and has contributed to maintain and create new highly qualified jobs at beneficiaries and suppliers. In terms of economic impacts, ENOVAL has the potential to decrease operating costs of airlines - one of the major cost factors for them, thus enhancing carriers' competitive position but also making travelling more affordable for European citizens. ENOVAL technologies are key enablers in supporting the traffic by indirectly contributing on the one hand to meet the citizens needs for mobility while on the other hand helped to increase the acceptance of such mobility impacts in local communities in the neighbourhood around airports.

After the end of the project, technologies investigated within ENOVAL will be further developed to a higher TRL and to advance the technologies from ENOVAL to dedicated technology demonstrators in CleanSky 2 and CleanSky 3, aiming at integration into the future propulsion systems and aircraft application with expected entry into service (EIS) date between 2025 and 2030.

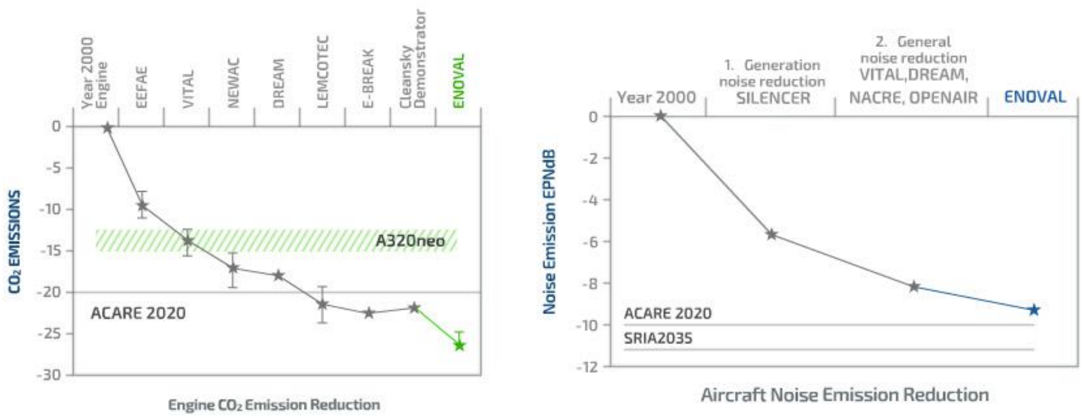
1. Project context and objectives

Ultra High Bypass Ratio (UHBR) propulsion systems with increased propulsive efficiency are amongst the best candidates for the next generation of short/medium range and long range commercial aircraft applications with an Entry Into Service (EIS) date of 2025 onward. The expected fan diameter increase of 20 to 35% (vs. year 2000 reference engine) is significant but can be accommodated within the limits of a conventional aircraft configuration. UHBR engines are a key technology on the roadmap of the Strategic Research and Innovation Agenda (SRIA) to meet the challenge of continuously reducing aviation-related environmental impact in the face of ever-increasing demand.

The ENOVAL project concentrated on geared ducted turbofan engines, which are considered the next generation of commercial aircraft applications with an entry into service date of 2025 onward. It developed technologies for the low pressure system to enable ultra-high by-pass ratio propulsion systems (12 < BPR < 20) with ultra-high overall pressure ratio (50 < OPR < 70).

The overall objective was to reduce CO_2 emissions and perceived noise of future aero engines and successfully validate innovative technologies at component level (i.e. up to TRL5):

- CO_2 reduction by 5% within the project alone achieving a cumulated CO_2 reduction of 26% for long range applications compared to technologies representative of year 2000 and including the achievements of past and currently ongoing projects such as EEFAE, VITAL, NEWAC, DREAM, LEMCOTEC and E-BREAK. For short/medium range turbofans the CO_2 reduction will be 3% alone achieving a cumulated CO_2 reduction of 24%.
- Overall reduction of engine noise emission by 1.3 EPNdB alone achieving a cumulated reduction in the range of 9 EPNdB, including the achievements of Silencer, VITAL, DREAM and OPENAIR. The engine noise reduction of ENOVAL will be included in the CleanSky 2 Technology Evaluator for a final assessment.



- ***Figure 1: Contribution of recent EU projects to CO_2 and noise reduction***

In order to achieve these overall objectives, innovative low pressure spool technologies with their specific individual contributions have been defined, which – as an overall purpose of ENOVAL – were successfully validated at a component level up to TRL5. The 5% reduction in fuel burn comes from 5% higher propulsive efficiency and 1.5% better module efficiencies compensating the 1.5% increase due to weight and drag. The noise reduction results from a 1.1 EPNdB jet and fan noise improvement complemented by LP turbine noise reductions.

ENOVAL's high level fuel burn and noise objectives will be enabled by the following three breakthroughs and contributing technologies:

- Expanding the design space for turbofans up to BPR 20
    - Novel very low pressure ratio fan module design features, such as advanced fan blades optimised in numbers, shape and weight together with new light weight Intermediate Case and new passive acoustic devices in the fan module
    - Holistic design concepts for shorter and thinner nacelle with enhanced integration of engine, pylon and airframe to counter the penalties of additional weight and drag

    - Improved LP-turbine designs for direct drive solutions including novel aerodynamics, noise liners and materials for increased temperature.
- Enabling a geared fan drive system for the very large, long range engines
    - Optimised gearbox heat management to reduced windage losses
    - Advanced high load high speed booster including casing treatments
    - Integrated improved aerodynamic, noise and mechanical design of Inter Turbine Case (ITC), high speed Low Pressure Turbine (LPT) and Turbine Exit Case (TEC) for reduced module length and increased performance
- Introduction of VAFN to allow optimum stability and design for efficiency for low pressure ratio fans
    - Integrated aerodynamic and mechanical optimization
    - Optimised control strategies for operability and performance

An integrative approach was applied to achieve the above-mentioned objectives. Therefore, the impact of introducing single technologies into the overall engine system was continuously assessed, both on a propulsion system and aircraft system level while integrating results from previous programmes and projects. This was setting the basis for the ENOVAL developments.

The individual technology modules under investigation in ENOVAL and their impact were evaluated through studies and assessments based on three propulsion system platforms:

- Short medium range with optimum fan drive system
- Long range engine with optimum fan drive system
- Very long range geared fan

The technologies were tested and validated using major mechanical and aero-acoustic rigs in order to bring the technology readiness up to TRL 5.

After the end of the ENOVAL project these technologies will be further developed by the partners to a higher TRL. It is currently planned to advance the technologies from ENOVAL to dedicated technology demonstrators in CleanSky 2 and CleanSky 3, aiming at integration into the future propulsion systems and aircraft application with expected entry into service (EIS) date between 2025 and 2030.

2. Main S&T results/foregrounds

Given the large number of activities performed within the project corresponding to almost 2,700 Person-Months (PM) of effort, it is not possible to provide an exhaustive description of all project results. In this chapter, only the most significant results are briefly presented per sub-project (SP), making reference to the fulfilment of transversal expectations or challenges.

2.1 Assessment of ENOVAL Results (SP1)

Objectives of SP1

The overall objective of SP1 was to develop and provide the detailed specifications for the propulsion system platforms, the requirements for the other SPs and to assess the benefits of the ENOVAL technologies by integration on system level (propulsion system and overall aircraft level) in the whole range of the investigated BPR up to 20.

The high-level objectives of SP1 were to:

- Provide an overall consistency of component and technology specifications for ENOVAL. In particular to
  - Define and specify the three conceptual engine platforms (Medium Turbofan Engine, Large Turbofan Engine and Very Large Geared Turbofan Engine) capable to meet both the ENOVAL objectives and the top-level aircraft requirements for the three different applications (medium, long and very long range missions).
  - Define and provide corresponding reference aircraft for each of the selected ENOVAL conceptual propulsion system platforms.
  - Define perimeter, metrics and methods suitable for an assessment at overall aircraft level.
- Monitor and evaluate the technology status on engine-aircraft system level and assess the final achievements against the ENOVAL objectives and ACARE targets and SRIA roadmap. Further, to assess the technical feasibility on overall engine and aircraft system level including economic and environmental aspects as well as applicability in product and services.
- Take the benefits of the technologies developed in ENOVAL to the next level by exploring technologies and aero-engine concepts beyond the ENOVAL EIS time frame.

Together with experience gained in previous FP6 and FP7 projects NEWAC, VITAL, DREAM, OPENAIR, E-BREAK and LEMCOTEC, SP1 was integrating the technologies developed in SP2, SP3 and SP4 on a whole engine and aircraft system level to achieve the ENOVAL targets. An important role of SP1 was to provide a consistent monitoring of the technology status against the ENOVAL targets by performing intermediate and final technology evaluations and iterations. For this purpose, an "Expert Advisory Group" was set up consisting of one expert from at least each of the platform owners plus DLR and Airbus who committed to participate.

In addition, SP1 included low technology readiness level (TRL2) activities aiming at maturity after 2030 addressing low pressure system heat sinks, hybrid fan drive, variable secondary flow devices, and variable fan and turbine systems to provide more radical solutions allowing to achieve the SRIA targets beyond 2020 and to provide mitigation plans in case the stated objectives would be achieved only partially (for this, please refer to chapter on Future Technology Concepts).

Results of SP1

The integration of the results for the ENOVAL technology development is based on three specified study power plant concepts. Together with the Expert Advisory Group the SP1 team defined the top-level aircraft requirements (TLARs) and developed corresponding reference aircraft layouts for the three intended engine platforms for a Small-Medium Turbofan (S-MT), a Large Long Range Turbofan (LLRT) and a Very Large Turbofan (VL-GTF). The related engine configurations and design data have been established in an iterative approach. Additionally, three families of new aircraft were designed to exploit the benefits of the ENOVAL technologies.

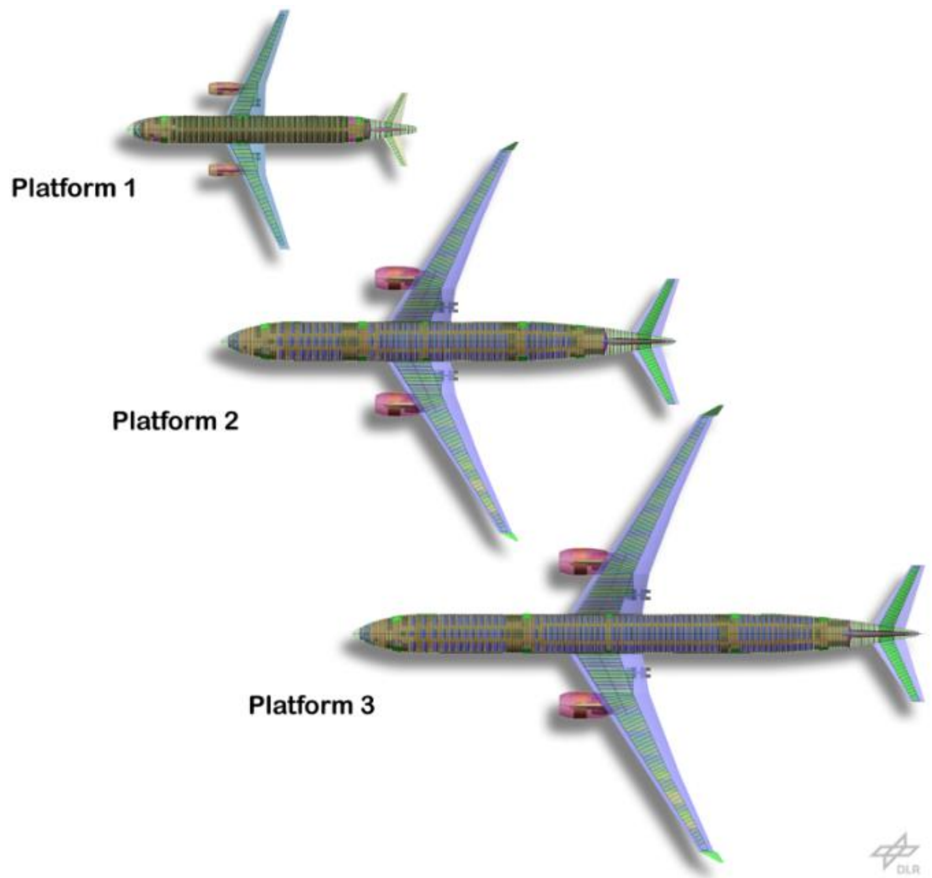


Figure 2: ENOVAL aircraft platforms

All three engine platforms are based on a geared engine configuration. Within an integration study starting from the main requirements and constraints a suitable gearbox configuration has been evaluated for each engine platform.

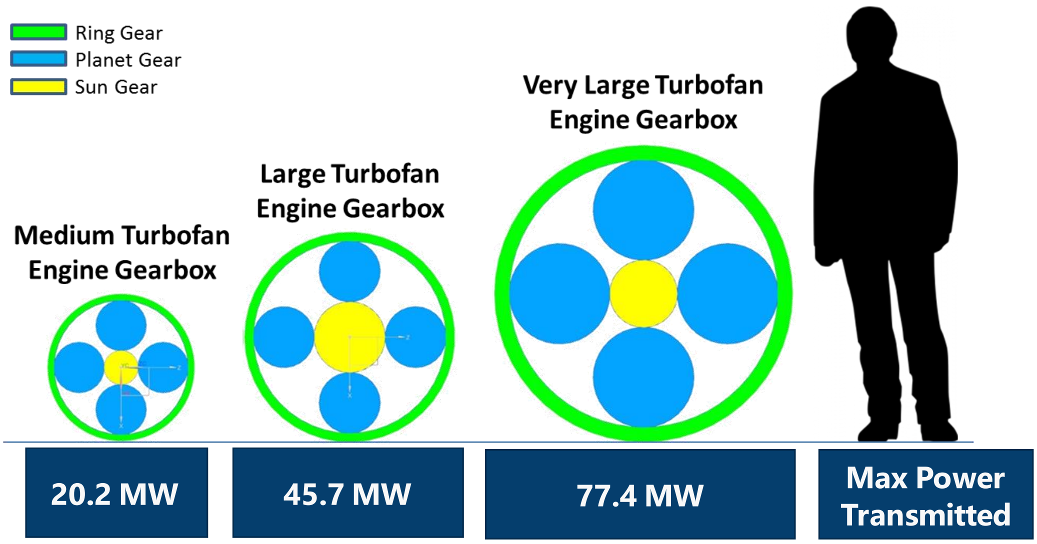


Figure 3: Gearbox study

	Small-Medium Turbofan	Large Turbofan	Very Large Turbofan
Thrust take-off	85.8 kN / 19.3 klbf	252 kN / 56.7 klbf	340 kN / 76.5 klbf
Configuration	1-Gear-3-8-2-3	1-Gear-4-11-2-4	1-Gear-3-9-2-4
Fan diameter	2.03 m / 79.8 in	3.17 m / 124.6 in	3.84 m / 151.1 in
Fan pressure ratio (Top of climb)	1.36	1.51	1.41
Bypass ratio (Mid Cruise)	16.2	16.2	16.0
Overall pressure ratio (Top of climb)	54.7	73	59
Specific fuel consumption (Mid Cruise)	13.98 g/kN/s / 0.494 lb/h/lbf	13.73 g/kN/s / 0.485 lb/h/lbf	13.47 g/kN/s / 0.476 lb/h/lbf
Engine weight	4000 kg	10136 kg	11625 kg

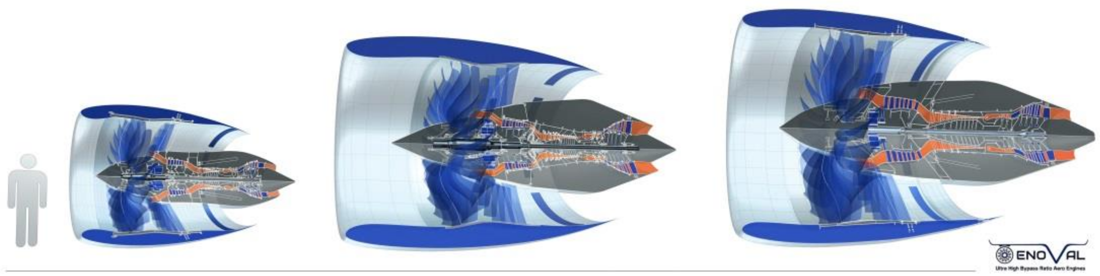


Figure 4: ENOVAL engine platforms

The overall assessment of the specific achieved technology impacts shows that the ENOVAL project significantly improves the CO_2 and noise emissions particularly for the Large and Very Large Turbofan configuration. Whilst the three engine platforms have been optimised for minimum fuel burn, all three are also fundamentally low noise designs. All are low specific thrust, delivering low jet velocities and low jet noise. The engine architectures with a power gearbox, with low speed fans, can also be expected to be beneficial for engine noise. The ENOVAL objective of a reduction of engine noise up to -1.3 ENPdB is achieved.

The impact on the CO_2 emissions of ENOVAL engine technologies based on an assessment on aircraft level shows that the ENOVAL objectives of a reduction in terms of fuel burn up to -3% (corresponding to -24 % cumulated vs. technologies representative of year 2000) for short/medium range turbofans and up to -5 % (corresponding to -26 % cumulated vs. year 2000) for long range applications are well met or surpassed.

Fuel Burn Saving (%)	Small-Medium Turbofan	Large Turbofan	Very Large Turbofan
ENOVAL Objectives	-24.0	-26.0	
Impact of ENOVAL engine technologies on aircraft level	-25.4	-29.2	-32.0

The assessment of the overall improvement of CO_2 emissions on whole aircraft system level based on cumulated engine technologies (incl. LEMCOTEC, E-BREAK and ENOVAL) and also accounting for airframe technologies are close to or even surpass the SRIA 2020 target of -36% reduction:

Fuel Burn Saving (%)	Small-Medium Turbofan	Large Turbofan	Very Large Turbofan
SRIA 2020 Target	-36.0		
Impact of engine and airframe technologies	-31.2	-40.4	-40.4

The integration of the propulsion system platforms into their respective aircraft requires specific knowledge and experience concerning engine-airframe integration. While all ENOVAL partners have specific know-how in this area, it was desirable to include a more global view of the whole system "aircraft- engine" and to make use of the experience of an airframe manufacturer, namely Airbus, as they have a product portfolio that is in accordance with the range of applications in ENOVAL. For this purpose, an "Expert Advisory Group" was set up, consisting of experienced engineers providing feedback on issues focusing on airframe-engine integration issues. The group met regularly and attended the full consortium meetings. Feedback and inputs of the Expert Advisory Group have been considered by ENOVAL and have been an important contribution to guide the work.

2.2 Fan Modules and Nacelle for Small to Medium Size Engines (SP2)

Objectives of SP2

The main objectives of SP2 were to mature up to TRL 4-5 an innovative fan module for UHBR engines (By-Pass Ratio between 15 and 17) dedicated to short and medium range aircrafts applications and to mature some associated technologies that contribute to the improvement of such innovative fan module (air intake technology, acoustics concepts and technologies, VAFN). Within this framework, SP2 aimed at exploring the design space of low pressure ratio fans and integrated OGV and to determine the optimum point for a given short to medium range engine mission as provided by SP1.

Fan module objectives were

- To obtain aerodynamic and acoustic experimental tests results concerning fan module at TRL5 specifically designed for turbofan thermodynamic cycles with By-Pass Ratio between 15 and 17 and aiming next ducted engine generation (EIS 2020-2025).

- To validate the fan module adiabatic efficiency and the effective perceived noise levels, associated to these unusual fan characteristics and increased BPR thermodynamic cycle.

Nacelle objectives were:

- To select the inlet acoustic liners and VAFN concepts needed by low pressure ratio fans through theoretical evaluation.
- To obtain a first validation of the acoustic damping quality of the selected liner.
- To obtain a first validation of the mechanical viability of the selected VAFN concept.
- To validate experimentally an optimised air intake aiming at improving operability and efficiency (consistent with reduction of fuel consumption).

The overall objective is to improve the aerodynamic and acoustic performances of the fan module by +0.75% (fan adiabatic efficiency) due to the effects of a lower fan pressure ratio, optimisation obtained thanks to the VAFN use and 3D aero-acoustic optimum design.

Results of SP2

First, the design space, from an integrated point of view, has been widely explored using quick analysis tools to select relevant concepts that seem promising and easy to integrate in tested fan module and minimizing impact on installation. This activity lead to challenging design requirements answering fuel saving and noise reduction targets at engine level.

For the fan module, a new low speed fan module was designed. The numerical evaluation showed that the initial performance and noise objectives can be achieved, and even exceeded. Some passive systems, mainly dedicated to noise reduction but also to operability margin improvements, were designed for testing purposes. This hardware was manufactured and integrated in the Ecole Centrale de Lyon aero-acoustic test bench. The ENOVAL test vehicle was composed of 5 sub assembly parts displayed in Figure 5:

- The inlet coloured in brown
- The fan casing coloured in green
- The fan rotor coloured in blue
- The aft fan coloured in pink
- The existing parts used during the commissioning tests in white

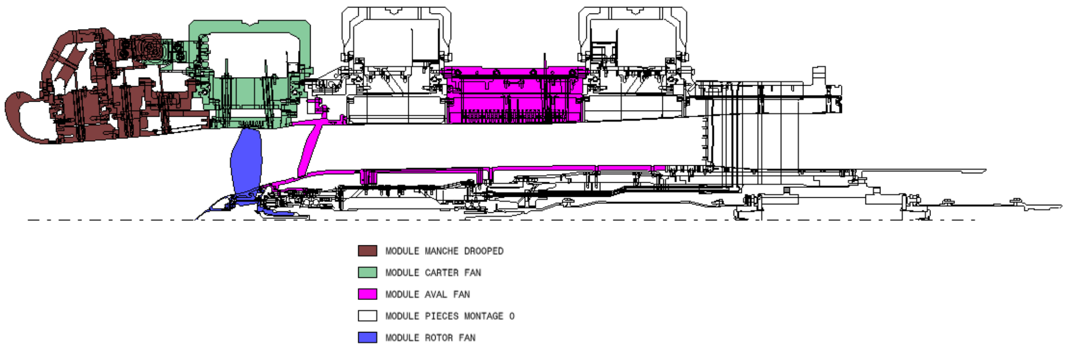


Figure 5: MARLYSA cross section and sub modules description

Most of the casings were made of aluminium to limit their cantilever contribution. However, the aluminium is subject to deformations during the manufacturing process. Therefore, a specific machining process has been established employing step by step machining and intermediate controls in order to limit and correct the deformations. At the end, the machining of these parts took more time than initially scheduled and some parts have been manufactured twice because of the deformation issue.

Dedicated advancement measurements were set up, not only to assess the TRL improvement, but also to acquire detailed data for physical understanding of unsteady phenomena. Those test results are providing an accurate data base for technology maturation.

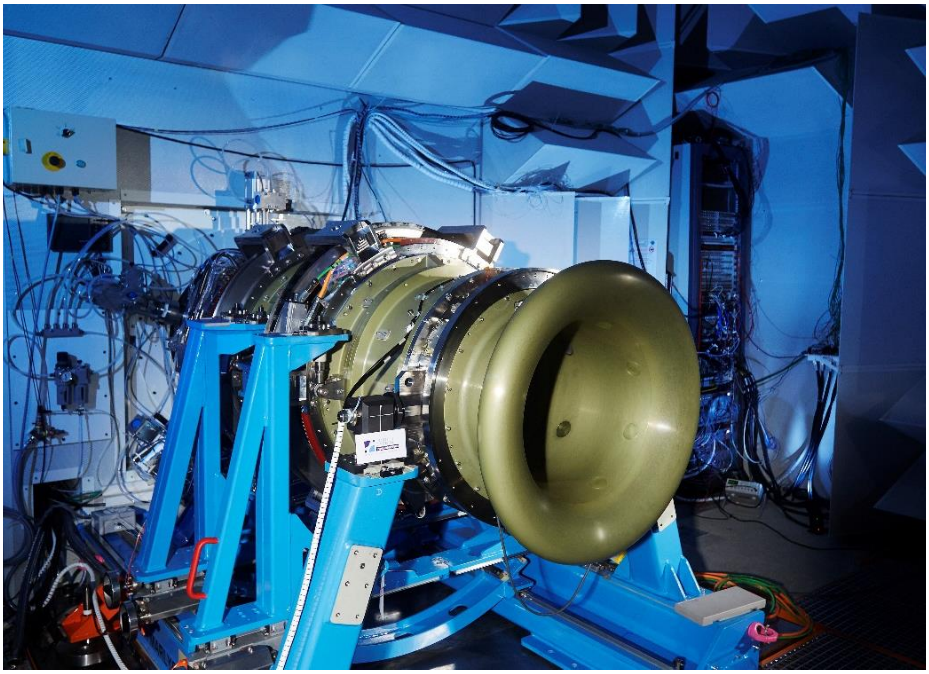


Figure 6: MARLYSA final assembly at ECL

When writing this report, all the tests are not performed yet. Nevertheless, pretest predictions, calibrated with previous test on this rig with a "reference" configuration, are showing that the performance objectives will be reached with a very good level of confidence:

- Operability: 15% throttle margin capability
- Isentropic efficiency: 0.8% improvement
- Acoustic: 1.3EPNdB reduction per certification operating point (Approach, CutBack, Sideline)

New acoustic treatments are required for shorter inlet where integration space is highly constrained. Two concepts ("Soft Walls" and Electrodynamic/Distributed skin") have been assessed in parallel. For the "Soft Walls" concept acoustic tests have been made in CEVAA, Rouen, France with different materials and different thicknesses which showed its efficiency, but also its limits at certain flow conditions. Safran Nacelle investigated acoustic thin absorbers to reduce low frequencies. Finally, an electrodynamic skin of only 25mm thickness and made of of 30 speakers and 120 microphones was successfully designed, manufactured and tested in NLR facilities. These tests successfully demonstrated the ability to attenuate low frequencies, with a very good adaptability. The attenuation peak can indeed be controlled in changing the electrical circuit settings as shown in Figure 7. It means that this kind of liners can be adapted to the engine power rating to maximize the noise reduction according to the aircraft flight phase.

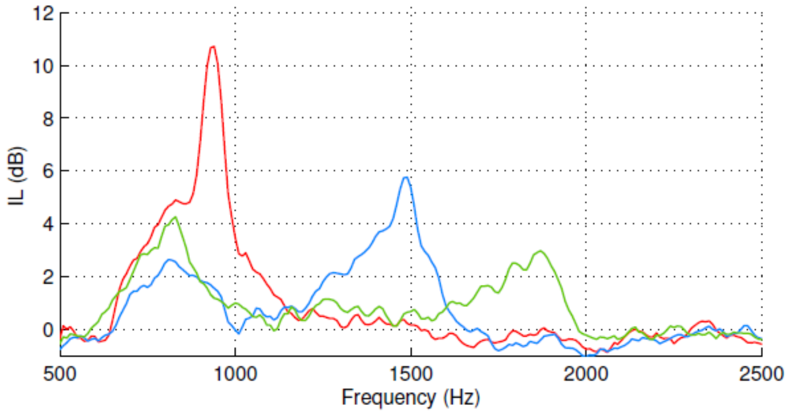


Figure 7: Example of measured acoustic attenuation

For VAFN, the challenge is to integrate this technology within the very slim nacelle lines of UHBR engines. To address this challenge, SAFRAN Nacelles have developed a new concept devoted to BPR between 14 and 18 that is compatible with new thrust reverser design for UHBR (translating cascade) and associated aerodynamic line geometry. This new concept uses doors located in the aft part of thrust reverser translating cowl. They are open to create additional nozzles (one between each door and the fixed structure). An aft ring preserves the geometry of the main nozzle which remains untouched. This VAFN concept (SAFRAN Nacelle proprietary) is called aft door concept.

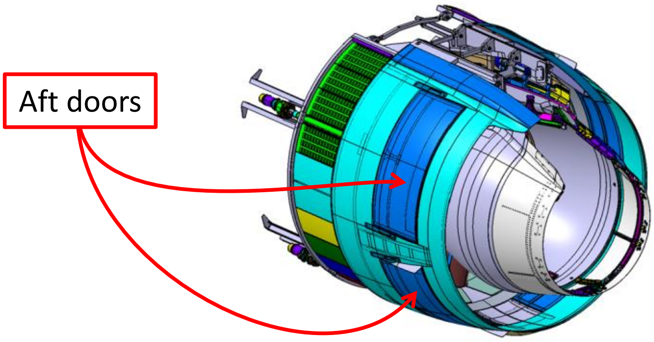


Figure 8: Thrust reverser with VAFN aft doors

The door mechanism was manufactured by Safran Nacelles at full scale and tested for different normal and abnormal conditions. Its robustness was demonstrated. The conclusion of these tests was that the system appears to be very robust and has proven a TRL3 maturity level for this kinematics mechanism. A go forward plan could be set up to increase the load cases and the integration representativeness (material interfaces).

The technical objective of an optimised air intake was to address FOD management and distorted air inlet pattern for engine operability improvement. The air intake was designed and optimized to match air flows encountered in the compressor test module that was studied in SP4. Numerical simulations were performed to minimise air inlet losses induced by highly distorted air flows. The air intake walls are made of composite materials. A new kind of mold was investigated, faster and cheaper to manufacture, and adapted to the project because it is used for very small series. This technology was successfully used to manufacture the parts with simple lay-up surface. During a dedicated meeting, the TRL 3 has been validated during the ENOVAL project. The tests of the demonstrator will be conducted within CleanSky 2 and it is expected to reach TRL 5.

Figure 9: Picture of the distorted air intake demonstrator

To sum up SP2 results, ENOVAL objectives in terms of maturation of low pressure ratio and low speed fan for short and medium range aircrafts applications have been reached. Further work is still needed to go on maturing these technologies, but an important step is already made thanks to ENOVAL project.

The summary of the TRL evaluation within SP2 is the following:

	TRL status	
	Initial	Validated End of ENOVAL
Low pressure ratio and low speed fan design for short/medium range application	2	**4**
Integrated OGV for UHBR fan	2	**4**
"Soft walls" liner	2	**3**
Active acoustic liner	2	**3**
VAFN concept	2	**3**
3D optimized air intake	2	**3**

Figure 10: Summary of final TRL evaluation

2.3 Fan Modules, Nacelle and Intermediate Case for Large Engines (SP3)

Objectives of SP3

SP3 aimed at developing technologies aimed at improving efficiency and reducing noise with respect to the large fan engine primarily aimed at long range aircraft. Technologies developed within SP3 included an advanced large low pressure ratio fan module and a novel intercase with optimised OGV. Studies have been conducted to determine the requirements for a new VAFN integrated into the nacelle optimised for the large engine, which will incorporate advanced acoustic liners.

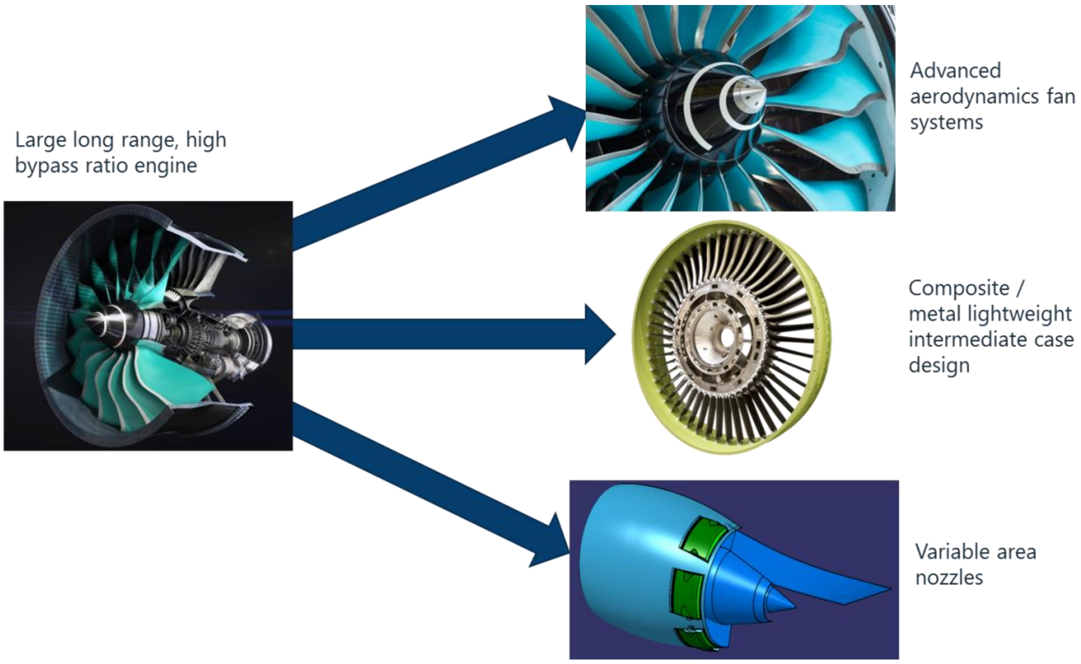


Figure 11: Schematic overview of the SP3 Objectives

Fan module objectives were:

- To explore fan system design space and set a preliminary configuration.
- To design an aerodynamically optimised Fan-module for UHBR engines aiming at a BPR of 16-18.
- To provide experimental noise data for design tool validation by applying advanced measurement techniques to an engine representative rig.
- To manufacture, build and rig test the novel UHBR fan module up to TRL5.
- To assess methods and design rules currently used for the design of HPBR fan modules against experimental data obtained in the WP and outline the way forward improved methodologies for the design of UHBR fan modules.

Intermediate Case objectives were:

- To develop technology for the by-pass structure of an Intermediate case to enable a further 15% weight reduction compared to current state-of-the-art. The base line is the VITAL- composite fan OGV improved with light weight cores, innovative metal to composite interfaces and potentially integration of noise reduction liners in or between OGVs.
- To verify the technologies at a TRL 5 level in a mechanical test relevant for the large engine platform.
- To contribute to an overall reduction of CO_2 emissions by 1% through reduced engine weight.

Large Engine Nacelle/VAFN System objectives were:

- To develop the requirements for variable area nozzles VAFN technology for large engines/nacelles of long range aircraft, for improved powerplant overall performance and minimised nacelle weight increase compared to a conventional nozzle.
- To integrate VAFN-development requirements based on overall architecture, the high level specifications and quantify benefits.
- To identify system integration requirements.
- To define means of controlling nozzles (engine/nacelle interaction) and of varying nozzle areas.
- To define means of actuation, supply of energy sources.
- To integrate Thrust Reverser with Variable Area Nozzle and derive benefits in comparison to two separate systems.
- To improve impacts on aero smoothness, load sharing, engine compatibility, acoustic performance and reliability.

Results of SP3

In the area of advanced aerodynamic fan systems, the first step was to conduct a sophisticated test vehicle designed and manufactured representing key LP system features. After the fan system has been designed based on the specification of the Large Engine Platform considering the integration with the airframe through automated optimization strategies in combination with 3D-CFD and FEM analysis.

This state-of-the-art aerodynamic testing conducted at the Anecom test facility in Berlin generated high fidelity performance, aerodynamic, stability and noise data. In order to take the sophisticated measurements required in this project, significant work was conducted to develop and deploy new, advanced measurement methods. DLR prepared and executed the acoustic measurements in the bypass section of the UFFA test facility. UoS developed and provided acoustic measurements technique to identify the relative source contribution from the rotor and the OGV. The data generated was then fed back into the predictive methods used to design these systems to enable highly effective design tools that can optimise designs for noise, performance and the environment. For this, a high frequency asymptotic approximation for the Eigen modes and Eigen functions for flow in a lined duct was developed by UCAM, which allows to calculate with the Green's function the numerical and asymptotic results for realistic swirl and shear.

The data has validated high fidelity and fast solver methods to evaluate the behaviour of low pressure ratio, low speed low pressure LP systems. Indications are that significant improvements to efficiency and noise emissions can be achieved and highlighted opportunities for further improvements that will be exploited under the CleanSky 2 programme.

Figure 12: Anecom test facility with an installed test vehicle

Intermediate cases contain the Outlet Guide Vanes (OGV). An opportunity was identified to optimise the light weight structures. Key features and capabilities were developed and validated including composite to metal joints, impact characteristics of composite components with light weight cores. An intermediate case (IMC) structure was designed and a full-scale demonstrator with a titanium hub frame, single configuration OGVs and an aluminium fan case ring was built. Mechanical sub-component testing was performed and finally, a full-size mechanical test was conducted by GKN together with SICOMP to prove the mechanical functionality of the assembled structure. Engineering methods for manufacturing, cure deformation simulation, FE-representation of complex mechanical joints and full field optical measurements of displacement were applied, calibrated and verified.

Figure 13: Full frame mechanical test to prove the mechanical functionality of the assembled structure

The test results and improving simulation models based on these results have been analysed. GKN performed an additional sub-component test where a single fan outlet guide vane was subjected to mechanical loads above the ultimate load. The final analysis to test comparison was found to be within 10% for stiffness and +/- 4% for first 5 vibration eigen modes. Limit loads were reached without any damage.

Variable Area Nozzles (VAFN) aid the implementation of low speed fan systems. Design studies of potential concepts were conducted, including challenges of integration. Detailed assessment was conducted of the aerodynamic & noise effects of the varying geometry. An aft door Variable Area Fan Nozzle (VAFN) concept with a segregated actuation system was selected in the early/mid ENOVAL phases to meet the requirements for area change, rate of actuation and accuracy. The design of the selected VAFN has been consolidated by Safran Nacelle and aerodynamic studies at different at different flight conditions have been carried out and the final aero performance was assessed. A middle door full scale prototype was manufactured and tested. The test campaign was completed with a positive outcome to support TRL4.

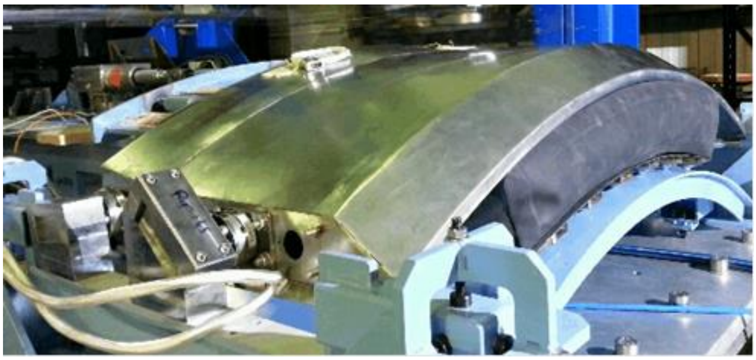


Figure 14: Actuation system testing

2.4 Low Pressure Spool Technologies (SP4)

Objectives of SP4

The main objectives of SP4 targeted at the different engine platforms studied in ENOVAL to mature technologies for high speed and low speed low pressure spool applications up to TRL 4-5 and to enable the ENOVAL overall goal of UHBR engines for long and short/medium range aircraft application. Within SP4 the different modules separated into PGB, LP Spool Compressor and LP Turbine (High and Low Speed) have been improved by integrated optimisation aspects.

High speed low pressure spool application objectives were

- To improve the PGB efficiency by 0.2%.
- To enable UHBR architecture with the design of an high load high speed booster with aggressive strut interaction upstream and downstream of the booster by keeping stability and efficiency.

- To improve LPT module weight up to 7%, reduce noise by 3 EPNdB and increase LPT efficiency up to 0.2% by integrated design optimisation of Inter Turbine Case (ITC), Low Pressure Turbine (LPT) and Turbine Exit Case (TEC).

Standard low pressure spool applications objectives were

- To improve LPT efficiency up to 1.65% by improved aerodynamic technologies, reduce noise by 3 EPNdB and improve LPT module weight up to 5%. This can be achieved by high efficient integrated airfoil design. In addition to this new materials and integrated design- manufacturing process improve the temperature capability of the disks by 50K and reduce manufacturing costs by 30%

Results of SP4

The fan for an UHBR application will be driven by the LP spool system. Depending on the application and a geared or ungeared architecture the LP spool can be divided into different modules. The LP compressor and the low pressure turbine for the ungeared configuration and in addition to this the transmission system for the geared one. The role of this SP4 was to ensure that the various technologies for the different low pressure spool modules and its applications will be developed to a TRL up to 5 to enable and support the ENOVAL targets.

Therefore, the low pressure spool was separated into the different modules PGB, LP Spool Compressor and LP Turbine (High and Low Speed). For geared applications, the transmission system, connecting the fan and the LPT, focused on technologies to reduce the power losses and resulting loss of efficiency. The technologies for the high load high speed booster (LPC) demonstrated on module level new technologies to secure TRL5 for introduction in next generation engines. Also, for the high speed low pressure turbine different technologies were tested on module rigs to demonstrate TRL5. Looking further into to the future, technologies with TRL up to 3 have been studied for the different modules. For ungeared engine configurations focusing on large engine application technologies for the LPT module were demonstrated for TLR5.

The use of a Power Gear-Box (PGB) to decouple LPT and Fan speed in geared architectures results in several advantages at engine and components level. Firstly, the possibility to reduce the fan speed, allowing high BPR and reducing acoustic emission; secondly the possibility to increase the speed of low pressure spool, resulting in a more compact and efficient low spool. Nevertheless, when large turbofan engines are considered the gearbox operates a great power. Dynamics of such complex systems is difficult to analyse due to multi-body flexible parts and multiple moving contacts. A thorough dynamic study is mandatory to assess any possible challenge, also in transient conditions and involving high-frequency excitations.

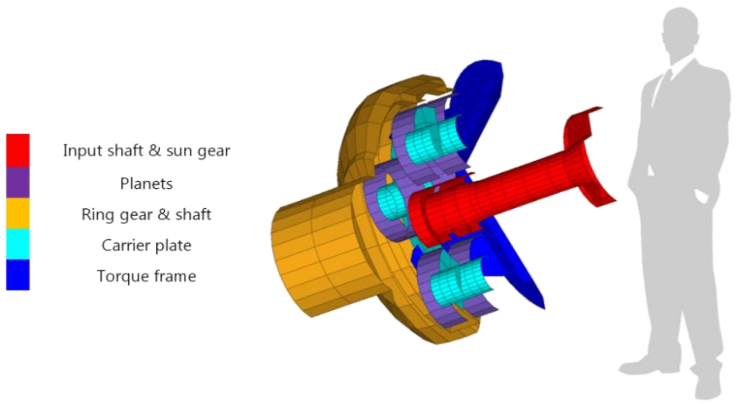


Figure 15: Power Gear-Box for the very large geared turbofan: rendering of the advanced 3D model for the transient methodology in the high-frequency field

To cope for such needs, special methods were needed. As standard centerline models and even state-of-the-art methods based on 3D are inadequate for the high frequency domain a new dedicated advanced methodology needed to be developed. Therefore, from the analytical point of view the 3D FEM components were optimised and reduced and also the system assembly via advanced contacts in 3D environment was developed, keeping the dynamic transient capability. This analytical study was accompanied by representative epicyclic PGB for very large geared turbofans defined, on a preliminary design level, as a star configuration. With those generated test data, the analytics were calibrated, and the key results were compared to a small to medium range application from the legacy. Within the project TRL 3 has been achieved. This innovative methodology was applied on different PGB application. The general conclusion drawn for PGB for very large geared turbofans shows a lower risk associated to transient high frequency dynamics, with respect to the usual smaller applications. It is possible to notice that from the Overload (OVL plots) and significantly higher modal density with respect to the usual smaller applications, leading to a more careful and difficult dynamic design for larger PGBs. Many other impactful studies like this can be carried out on new architectures by exploiting the method.

The gearbox of large turbofan engines operates at great power and has a direct impact on net power transmitted and PGB power losses. Research focused on experimental investigation and numerical analysis of the gearbox load-independent losses. For this purpose, a new test rig was designed and tested. Focus of the work was the investigation of gearbox load independent losses. In a second rig the aspects of meshing gears were studied. The most complex test article (an epicyclic test article) generated high quality data of a PGB configuration.

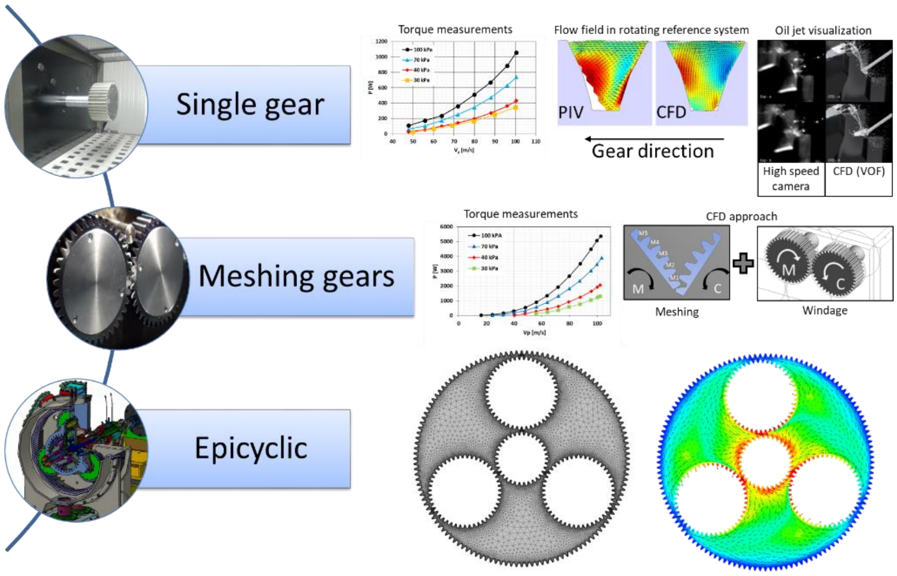


Figure 16: Overview of the test rigs and the corresponding analytical approach

In parallel a pre-design tool to find the best PGB configuration was established, and a CFD code was optimized to account for the complex system of a multiphase flow with rotating components. An advanced methodology with reduced 3D FEM analytic efforts was developed to study the dynamic behaviour of PGB as a complex multi-body module with moving contacts. With the measurement data gathered in the test rigs, CFD simulations were validated focusing on unsteady moving mesh approach for meshing and steady multi frame of reference approach for windage losses.

With all the test results and improved analytical methodologies, it is now possible to have a good prediction of the PGB configuration with improved efficiency already during the concept design phase of a new engine.

The low pressure compressor (LPC) is an engine component designed to prepare air pressure, temperature and flow velocity after fan and before entering to high pressure components. To drive such system in a geared configuration, the spool speed of LP-compressor is more than 2 times higher than in an ungeared version which leads to new challenges in designing such module.

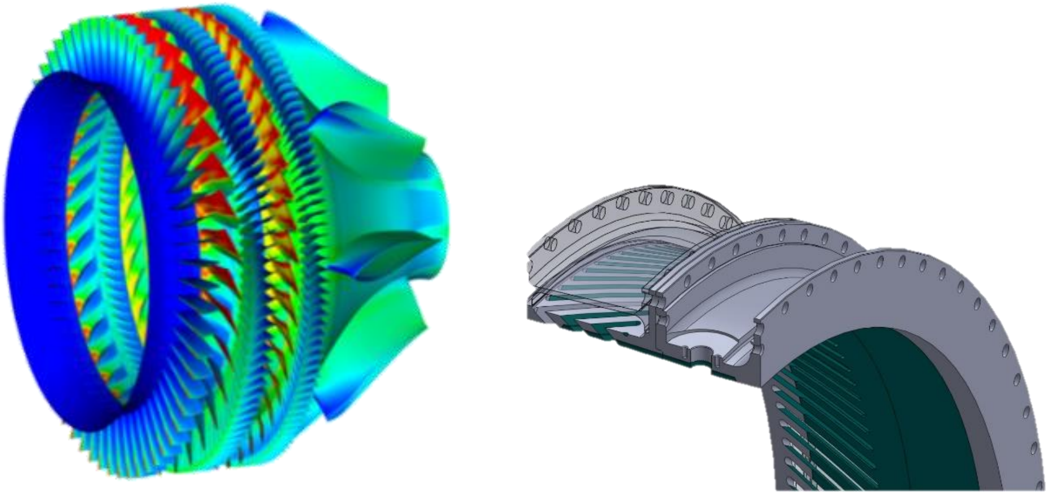


Figure 17: Transonic Aerodynamics & Casing treatment

To address the challenges as set out above, a new test rig was designed. The architecture of such a high speed booster was studied and designed using a Variable Stator Vanes system but also single stage machined titanium rotor. Upfront the final testing of such a rig, partial testing, like a maturity test of the Variable Stator Vanes has been performed to validate capability to introduce it on engine environment. Also manufacturing process had to be tested upfront for the used Blisks. The test rig was highly instrumented using also telemetry for the rotating frame. Detailed studies have been performed hand in hand with CENAERO and CIAM to study unsteady phenomenon on one hand and to introduce casing treatment on the other hand. As a result, CENAERO has developed a new methodology to assess flutter stability analysis applied to the high-speed booster. With respect to casing treatments, several tests have been successfully performed on CIAM C3 test bench before end of May 2018, generating high quality results for Booster mapping, deep surge and high speed investigations as also different Casing treatments.

With these results a higher maturity through test in engine environment could be shown. The aerodynamic demonstration at realistic inlet conditions proved the increased performance of this design and the introduced technologies. In addition, the robustness at transient and complex phenomena such as surging and rotating stall have been shown, accompanied by the analytics.

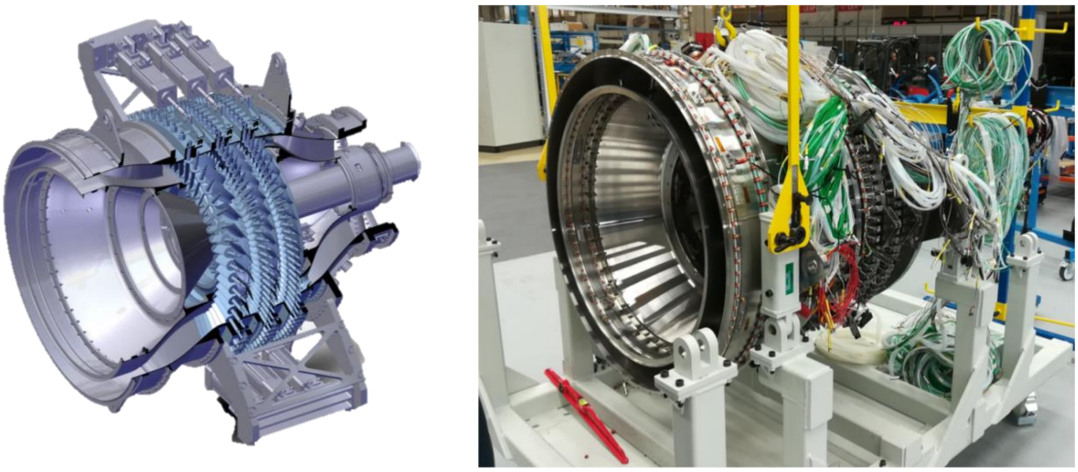


Figure 18: High Speed Booster Test vehicle: CAD model (Left), final assembled Rig (right)

To meet the challenges of the required higher-pressure ratio and the higher complexity for the LPC without compromising must efficiency and stability new innovative technologies as casing treatments, 3D swept blades, 3D blade platforms and leakage reduction features are integrated in the LPC module. Safran Aero Boosters supported by GDTech has designed and manufactured a full-scale LP compressor and a detailed investigation of the demonstrator has been performed at the Russian CIAM institute in Turaevo (Lytkarino). This required a noteworthy cooperation effort for the design of some main devices to enable the test.

Tomorrow's Low-Speed LPT modules driving High-BPR Engines are required to have an increase of efficiency and reductions in weight and noise to compensate the increase in overall propulsion system weight and dimensions due to the increased engine BPR. Industries require to convey and integrate technologies coming from past and ongoing research activities into demonstrator vehicles, that will run in similitude conditions to demonstrate technology readiness. Within ENOVAL several technologies were applied such as high stage loading aero design concepts, highly efficient 3D airfoils with reduced secondary flows, investigation on clocking and unsteadiness effects and the application of low noise design concepts.

During the ENOVAL project analytical studies in 2D and 3D were done to address technologies allowing aerodynamic improvements and noise suppression. These results were used to design rigs, addressing the different technology aspects. The rigs were a multistage rig representative of middle and rear LPT stages, a representative multistage rig to validate acoustic improvements and finally a specific noise module designed for high quality measurement. All rigs were highly instrumented to generate high quality measurement data for tool validation. After the first multistage rig test was run successfully at CTA, the second rig was also designed for 1.5 stages for the evaluation of trailing edge (TE) edge and 3D design within a multistage environment on the NGV performance. The tests for the second rig were performed successfully in CTA facilities in late 2016. With the results of both rigs, the potential of two novel technologies for noise reduction has been demonstrated: Optimised Acoustic Coupling (OAC) and 3D optimized vane shape.

The impact of machining parameters on surface integrity of machined disks normally needs upfront a process validation to get surface conditions not impairing fatigue response. These is proven by testing at different scales (material tests, rig tests…) and needs to be repeated for each new material. At the beginning of this project, no mechanical tests existed to demonstrate fatigue response of machined components and qualifying surface integrity of disks not giving sufficient information to develop material models and machining process modelling. To improve the understanding of the machining conditions and its impact on the material, machining trials designed to get intended damage on material were done. With the gained knowledge machining response of a different material, assisted by Process Modelling and confirmed by trials on test coupons could be established. Different levels of machining damage were applied: Base line & 2 additional surface conditions SC1 & SC2, aiming to assess their effect on fatigue response. Fabrication of tests pieces and surface integrity evaluation (metallurgical damage, roughness, residual stresses) was done. Based on the Fatigue testing on the "ad-hoc" machined tests pieces at elevated temperature including fatigue crack growth monitoring (IR thermography) was realized to get lives to initiation and to failure on specimens. This technique was especially invented in ENOVAL.

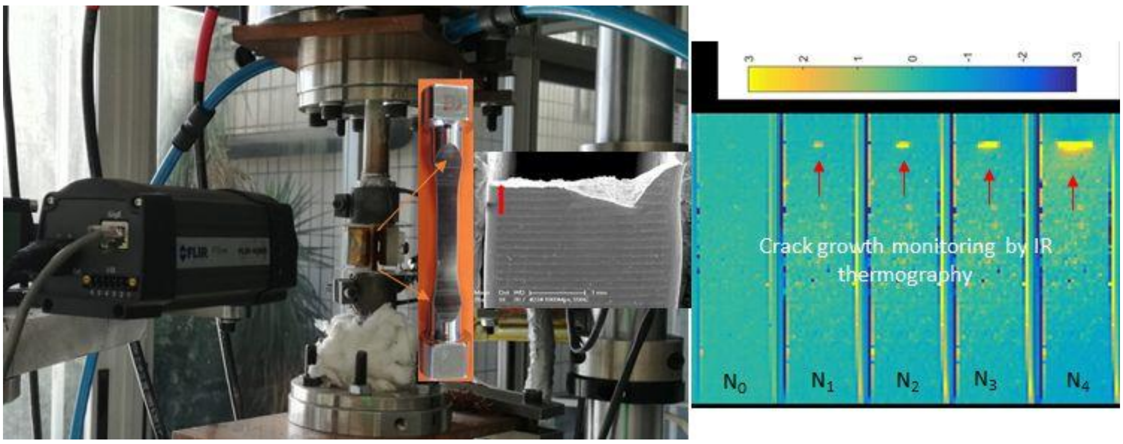


Figure 19: LCF testing with IR thermography for crack monitoring

For the classical LPT driving the fan directly, several test campaigns were established to test technologies with different improvement aspects.

Two multistage rigs representative of middle and rear LPT stages were designed and tested. The first rig focused on aerodynamic efficiency, the second one on acoustic improvements used for validation of such designs. In addition, machining effects on resulting surface integrity were tested on probe level to gain data for material models related to fatigue life. A new technology using IR thermography for crack monitoring was established.

Different test rigs were used to improve the overall efficiency of a direct coupled LPT. A dual-spool rig designed to investigate interaction of HP-LP duct with highly-loaded LPT stage was designed and built. The test generated high quality data for further validation of the aerodynamic design process. A second test rig focusing on the rear stages was used to validate highly efficient 3D air foils optimized for unsteady effects. Aspects of noise reduction were addressed in a newly built grazing flow rig. Liner performance assessed by aero-acoustic instrumentation was tested using hot flow conditions.

A Grazing Flow rig was newly designed to characterise the effectiveness of acoustic liners under hot flow conditions, representative of LPT operating conditions. The rig was established at UNIFI. The liner performance assessed by means of aero and acoustic instrumentation while a well-defined acoustic field was produced by a controlled source. The optimal liners geometry specimen identified by means of a dedicated numerical procedure; were realised in additive manufacturing and tested to substantiate the validity of the design strategy. The comparison of the measurement and analytics showed good agreement.

A high speed LPT configuration faces similar problems as a low speed LPT but needs to address higher rotational speed characteristics. An integrated ITC/LPT was designed using high fidelity methods. The highly instrumented rig produced high quality data for a better understanding of the complex flow regime in a representative ITC behind a real HPT increasing the efficiency of the LPT.

Each investigated technology validated the analytical tools. With those tools the design of Low Pressure Turbines which have to be more efficient, quieter, compact and lighter are able to design. The test rigs designed and built within the ENOVAL framework were excellent experimental validation vehicles featuring a modular design which now enables future investigation of promising technologies. Particular focus has been put on de-coupling front and rear stages in order to guarantee the best understanding of the phenomena of interest. The use of well-tuned acoustic liners is expected to guarantee a significant benefit in terms of LPT noise reduction and to enlarge the aero design space with positive impact on turbine performance and weight.

State-of-the-art design of the high speed low pressure expansion system still consists of individually optimised design of the Low Pressure Turbine (LPT) and the Turbine Exhaust Case (TEC) itself, where the boundary conditions between the specific modules are often simplified and based on assumptions. Neither the use of acoustic liners at the exit of the expansion system was investigated on demonstrator level, nor the validation of respective analytical tools before ENOVAL. As a start, a selection of high-fidelity methods was used to predict the behaviour of an integrated LPT/TEC design using noise reducing liners. It was focused on an integrated design process for a modified TEC to be integrated into state of the art LPT-rig. The TEC was designed and manufactured by GKN in close collaboration with MTU. It could then be integrated into a highly instrumented high speed LPT/TEC-Rig.

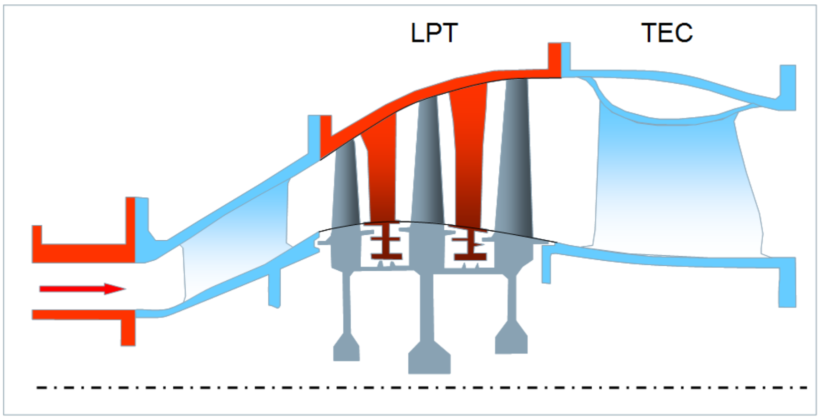


Figure 20: Integrated LPT/TEC Rig used for demonstration

With this, realistic flow conditions using the high-altitude test stand at ILA, University of Stuttgart, could be achieved. To test the performance of the acoustic liners of the TEC a back to back test, by changing only the acoustic liners was done. The acoustic impact has been measured by using high fidelity test equipment of the DLR. Measured and processed high quality data were used for validation and calibration of selected high-fidelity methods. The results generated by the rig test were used for validation of the analytical design tools. The post-processed acoustic data showed not only in the measurement but also with the validated analytical tools a significant noise reduction of the LPT exhaust. With this results an increased capability to predict noise emission is now available. It could be shown, that integrative design processes are needed to improve the overall performance of adjacent modules.

State-of-the-art design of the high speed low pressure expansion system still consists of individually optimised design of the Inter Turbine Case (ITC) and the Low Pressure Turbine (LPT) itself where the boundary conditions between the specific modules are often simplified and based on assumptions. Considering the interaction with the adjacent parts of the LPT, focusing here on ITC and LPT, integrated optimized design improves further aerodynamic efficiency. To prove the integrated design ITC/LPT design a stepped test campaign was established. Starting with a 2D cascade of the ITC and then increasing complexity stepwise to a nearly realistic flow in the TTTF rig those generated data were used for validation of the analytical methodology. Only the most complex test was part of the ENOVAL project. This last test gained the understanding of the complex flow regime in a representative ITC behind a real HPT. A new 360° traverse in front and behind the ITC has been designed to have a full set of experimental data to be used for further flow analysis. The rig was highly instrumented and contributed to further improvements by better understanding of the flow physics and interactions, increasing the efficiency of the LPT. It showed that capturing a realistic duct inflow is very important to understand all flow patterns. With this high-quality data generated during the test the validation of complex analytical tools for aerodynamic assessment of the flow through ITC and LPT could be established. New methodology for an integrated optimisation has been validated. With these results the development of an advanced ITC with improved overall efficiency can be realized.

An improvement of the efficiency of jet engines can be achieved by a weight reduction due to a smaller number of blades per stage. However, this usually also means that the aerodynamic loading per blade is increased. In the low Reynolds number regime these highly loaded profiles are typically prone to flow separation effects resulting in higher total pressure losses, and the efficiency of the jet engine is reduced to unacceptable levels. Therefore, boundary layer flow and separation phenomena have to be controlled. Different passive and active flow control methods have been developed over the last decades.

In this part of the ENOVAL-project an aerodynamically highly loaded TEC profile with active flow control was designed and is compared with a state-of-the-art profile. Compared to the state to art profile the pitch to chord ratio is increased by 44%, which leads to a remarkable reduction of the weight. Of course, this weight reduction should not be on the expense of a loss increase. As highly loaded blades tend to flow separation, which is typically accompanied by a total pressure loss increase, the design was equipped with active flow control (AFC) on the suction side of the profile. The experimental investigations could impressively demonstrate that high frequency pulsed blowing by fluidic oscillators is a very good method for this kind of profile to achieve low total pressure losses over a broad operating range, particularly in the low Reynolds number regime. Thus, the concept can be applied for the future design of highly loaded blade ducts, compressor and turbine profiles. The main benefit is a weight reduction without sacrificing the low total pressure loss level.

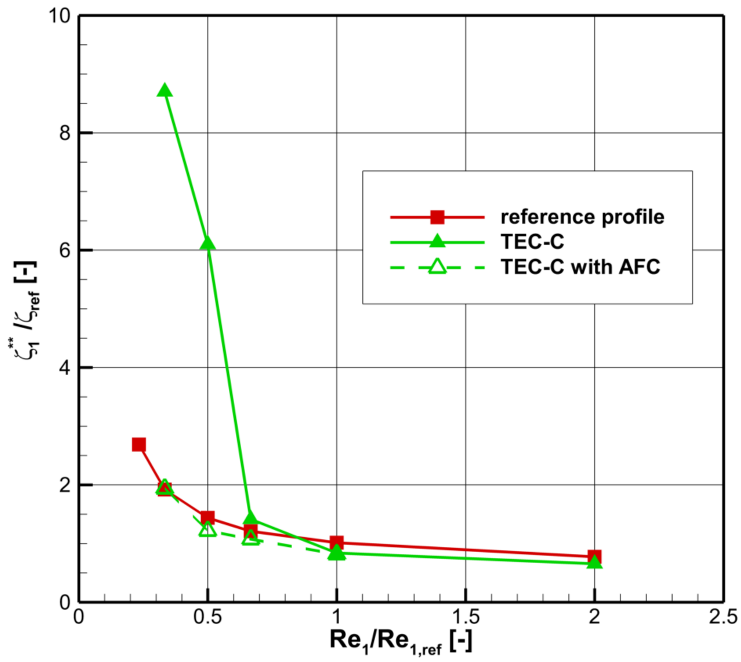


Figure 21: Integral total pressure losses with steady inflow for both profiles

2.5 Future Technology Concepts

ENOVAL focused on propulsor technology for turbofans which can enable development of future energy efficient engines with reduced noise and other emissions. The majority of the work was aiming for technologies at medium TRL (4-5) which, after further development, can be ready for integration into engines with expected Entry Into Service (EIS) between 2025 and 2030.

Looking forward to 2030-2050, there exist many more good ideas on how to bring engine propulsion and thermal efficiency closer to the limitations set by physics. To date, these ideas are not sufficiently refined to make it meaningful to develop a full implementation and bring them to a high TRL. Within ENOVAL, WP1.3 Future Propulsor Concept Studies has investigated specific technologies by a combination of correlations and aerodynamic calculations. A simplified approach has been taken with respect to the core system and aircraft to be able to assess the impact of the advanced technologies on fuel consumption, weight and noise reduction, and system integration aspects. The studies provide an outlook of four concepts for improvement of the low pressure system of engines aimed at EIS in the 2030-2050 timeframe. Three studies were exploring how flight mission variability in the low pressure system can be exploited, either using flow devices or by supplementing the turbine with electric power. One study was investigating how to reduce low pressure system flow losses and increase the efficiency benefit of rejected heat in future intercooled engines. The interpretation of the results obtained provides an overview of potential advantages and drawbacks of each technology and outlines the path of development for the field.

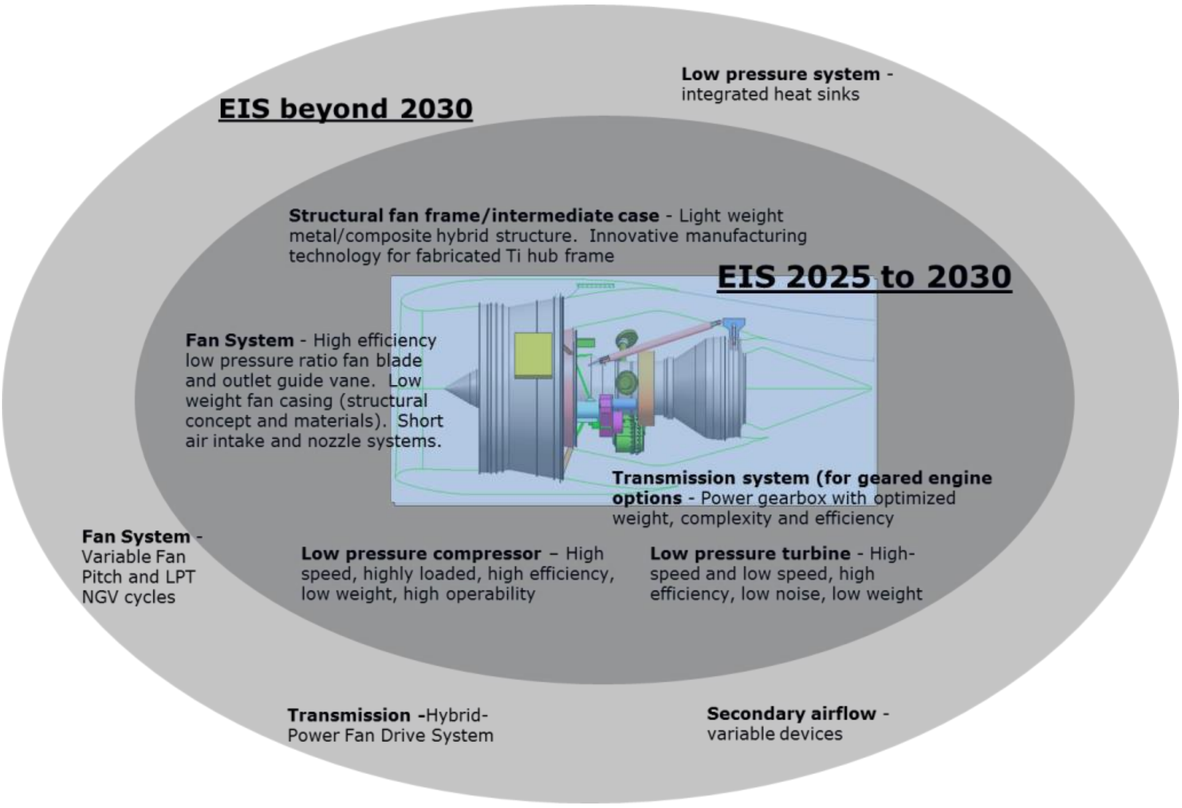


Figure 22: Typical ENOVAL engine platform with associated technologies being developed in SP1, 2, 3, 4

Within the subject of *Low pressure system integrated heat sinks* it was investigated how to reduce the low pressure flow path losses while rejecting heat from the core to intercool the compressor flow. Another path studied was how to maximise the benefit from the rejected heat by extracting work from the heat rejection process by employing a Rankine cycle engine.

Regarding the *Hybrid-Power Fan Drive System* a wide array of ways to integrate electric power provided by batteries to the propulsor to maximize reduction of the fuel consumption and noise while minimizing the bulk and weight of the turbine engine and the electrical drive were studied.

On the topic of *Bypass airflow variable devices* ENOVAL investigated the cycle and noise benefits from a variable pitch fan and variable fan nozzle using a cycle model calibrated by CFD simulation of the variable devices. The study showed how the devices can be used to control the choke and stall margin over the operation from take-off to top-of-climb.

Regarding *Variable Pitch Fan and LPT NGV cycles* a low pressure system with variability both on the propulsor fan and nozzle as well as the low pressure turbine nozzles was studied. In addition to providing increased control over propulsor aerodynamic margins, it provides the possibility to optimize the low pressure shaft speed variation over the mission cycle.

A way forward is described projecting the Entry into Service for the studied technologies and providing roadmaps for the development of the necessary technologies and relates these to on-going and upcoming projects in the European research arena. A clear recommendation is for the industry and EC to support upcoming engine concept evaluation projects based on the good results shown here and elsewhere. This is essential both for the long-term competitiveness of the European engine industry and to provide ways to mitigate the environmental effects of aviation. For industry these projects give an efficient way to outsource pre-competitive future engine studies to competent partners, allowing the industry engineers to concentrate on pressing development of the next generation of environmentally improved engines.

To improve the value of this type of correlation-based studies which are dependent on high quality data, ENOVAL also urges the funding agencies to ensure that coming projects will include TRL 3-4 validation experiments in the short term and to make preparations for demonstrations at TRL 5-6 a decade from now.

3. Potential ENOVAL Impacts

Already now as well as in the near future, aviation will have to tackle various challenges imposed by a continuously increasing global mobility demand from private as well as business travel and its environmental impacts. Fuel prices are expected to further increase, and emissions have to be continuously reduced to contribute to the global efforts against the climate change as well as the local impairments around airports.

Simultaneously, aviation is recognised as one of the top five advanced technology sectors in Europe. It provides close to nine million skilled jobs, directly and indirectly, and contributes 1,200 billion Euros to Europe's Gross Domestic Product. In an increasingly competitive market environment, together with the need for further emissions reductions, a huge effort is required to maintain global leadership for aviation in Europe and meeting the needs of its citizens.

During its 58-month duration, ENOVAL has developed and validated innovative technologies for Ultra High Bypass Ratio ducted engines delivering both additional CO_2 and noise reduction. The potential application range of those technologies is extremely wide, representing approximately 90% of the commercial market.

Supporting to protect the environment

Protecting the environment is one of the main drivers to further invest in the development of technologies to be the basis for new products in aviation industry, where the challenge is to continuously reduce aviation's environmental impact in the face of ever-increasing demand. The latest forecasts of the main airframe manufacturers Airbus and Boeing point out a still expected yearly growth average pace of 6.0-6.5 % of Revenue Passenger Kilometres (RPKs). Due to these prerequisites of the market, the pressure to reduce the emissions (C02, NOx, Noise, etc.) per passenger kilometre is even stronger in order to not further increase but even reduce the effect of e.g. global warming. In addition, reducing greenhouse gas emissions, fuel consumption and noise also goes with reducing operating costs and making future engines and aircraft more attractive both for airliners and citizens.

ENOVAL has strongly expanded the design space to higher BPR in order to increase the propulsive efficiency. Further, the results from past and on-going projects has been exploited to reach the overall target to reduce CO_2 emissions. The assessment of the overall improvement of CO_2 emissions on whole aircraft system level based on cumulated engine technologies (incl. LEMCOTEC, E-BREAK and ENOVAL) and also accounting for airframe technologies are close to or even surpass the SRIA 2020 target of -36% reduction.

In light of the expected development of passenger traffic, which is foreseen to double or even triple in the next 20 years, airport authorities will need to expand capacity to keep up with current and future demand. The environmental impact of aviation is most obvious at and around airports. In order to provide more capacity, airports have to address the pressure of local communities to manage and mitigate the impact of the traffic. Regulators will continue to take steps to reduce aircraft noise through the introduction of noise limits and flying restrictions, resulting in increased use of the most silent aircraft types. Europe's airports are consequently supporting further research and innovation on aircraft noise levels (as well as local air quality and the emission of greenhouse gases).

In some regions of the world, particularly Europe, airport communities have already strongly expressed concerns about the environmental effects especially due to noise of increased operations and airport expansion.

ENOVAL technologies together with further technologies developed in other European technology projects e.g. OPENAIR are key enablers in supporting the traffic growth in a manner well-accepted by local communities, and in addressing potential restrictions to be put in place against high noise aircraft. In this regard, ENOVAL has delivered significant contribution to reduce the environmental impact by delivering a value of -1.3 dB.

Addressing aviation market needs

In the latest news on Boeing's recent announcement to investigate the launch of a completely new aircraft in the market above the B737 class, the so called New Mid-market Airplane (NMA) unofficially already called B797 (225

– 270 pax), it is stated that the intended Entry Into Service date shall be 2025. This fits perfectly with the plan of ENOVAL technologies to be ready in 2020 at TRL 6 through a final validation within CleanSky 2 Engine ITD work packages which includes UHBR and UHPR engine concepts. Already during the preparation phase of the ENOVAL project the market of new commercial aircraft has evolved significantly with high volume orders for aircraft with new engine technologies (PW1000G or LEAP-1) and requests for further developments in fuel burn and noise reductions. Current market forecasts from Airbus Airbus (Global Market Forecast GMF for 2018-2037) or Boeing (Commercial Market Outlook 2018 – 2037) state the growth of passenger traffic at 4.4% vs. 4,7% and the need for 37,400 vs. 42,730 new aircrafts over the next 20 years. Strong indications and activities are evident that the trend for new engine architectures follows the outline in the SRIA for UHBR ducted turbofans (BPR >12): Rolls Royce is about to develop the "Ultrafan" engine concept. Therefore, the technology work which is performed within the ENOVAL project is considered to be highly relevant for the definition of the next generation of commercial aircraft engines.

Maintaining European leadership in aviation

In the last decades European aviation has successfully risen to a world leader through the combined efforts of public and private European entities, including major companies, SMEs as well as academia and research laboratories. ENOVAL has significantly contributed to maintain this leadership by bringing together European leaders in the aeronautics industry with high-class European research, successfully working together on innovative engine concepts. ENOVAL has strengthened the competitiveness of the European engine industry by enabling it to deliver the best products and services worldwide. This has strongly contributed to allow the industry to maintain a share of approx. 40% of its global market by retaining leading edge design, manufacturing and system integration capabilities and developing technologies up to full-scale demonstrators. This has also to be considered under the aspects of a highly competitive global market environment. Established competitors from the United States have subsequently been complemented by players from emerging economies such as China, Russia, India and Brazil. With the successful collaboration of key European players within ENOVAL and beyond, a solid base is laid for continued success and European excellence in the future market.

By preparing the the ground to move the technology from TRL4-5 that was achieved in ENOVAL to TRL6, collaboration between the ENOVAL partners led to numerous follow-up projects on key enabling concepts, technologies and systems. ENOVAL also included the investigation of low technology readiness level (TRL2) activities aiming at maturity after 2030 to provide more radical solutions allowing to achieve the SRIA targets beyond 2020 and to provide mitigation plans in case the stated objectives would be achieved only partially. Already during the project's duration and after the end of ENOVAL, the investigated approaches and concepts have been translated into new collaborative research projects in order to advance the technologies from ENOVAL to dedicated technology demonstrators in CleanSky 2 and CleanSky 3, aiming at integration into the future propulsion systems and aircraft application with expected entry into service (EIS) date between 2025 and 2030. In other words, ENOVAL contributed to draw a common roadmap for the technology adoption, enabling to produce engines meeting future environmental standards and commercial needs.

Small and medium sized enterprises represented almost 10% of the ENOVAL funding, a significantly higher relation than compared to the overall aero engine sector, which is mainly controlled by the large industrial aero engine manufacturers. ENOVAL supported these SMEs to improve their skills along the value chain and strengthen their role within the aeronautics industry. Several new business opportunities have been created as direct result of the SMEs involvement in ENOVAL, supporting them to grow into world-class companies.

The academic partners within ENOVAL have exploited their results mainly through scientific publications in high impact journals and world-renowned conferences. Their participation in ENOVAL strongly contributed to maintain their position in the international science, or even to improve. A high level of academic education was be maintained at the academic partners to educate high-level young engineers. Further, ENOVAL offered a unique opportunity to universities and research centres of participating in a work group together with industrial partners aiming at direct technology transfer. ENOVAL always had a clear intent of inspire current young generations towards a STEM (science, technology, engineering, math) career. This goal was met by the creation of several PhD positions for ENOVAL-related research as well as permanent academic positions.

Securing and creating European jobs

In 2014 for example, aviation supported 8.8 million jobs in the EU, and contributed over €621 billion to EU GDP. However, aviation is also important for the success of SMEs and tourism. €1 spent in the aviation sector generates

€3 for the overall economy; and for every new job in aviation three more are created elsewhere. EU rules also ensure that aviation workers are treated fairly.

During its duration and beyond, ENOVAL strongly contributed to strengthen the European Labour market by securing numerous jobs in Europe. Through ENOVAL, approx. 850 European jobs have been maintained directly at the participating beneficiaries in the field of engineering and highly qualified craftsmen on production sites. Also, ENOVAL indirectly contributed to European job creation at the involved project subcontractors. Moreover, ENOVAL created new employment opportunities by creating 6 jobs at partners as direct result of their ENOVAL involvement.

Contributing to airliners' economic efficiency

Fuel prices are an almost inalterable factor to be mainly addressed by more efficient aircraft and engines: In 2001, fuel costs represented 13% of the total operating costs, whereas today the percentage amounts to approx. 33%. Forecasts for 2031 see the percentage further increasing to 40%. Delivering engine technologies that will reduce fuel consumption will consequently make the European aviation industry more competitive and enable the sector to maintain its position against US competitors (and sometimes partners) who are making similar efforts. The European aviation sector will strengthen its leadership against newcomers who cannot break the technology barriers set out through decades of continuous R&D investments in Europe.

By reducing fuel burn by 5% compared to the year 2000 reference engine, ENOVAL has the potential to decrease operating costs of airlines - one of the major cost factors for them. Low cost carriers are in particular driving a strong demand in this direction. These operators have made important optimisations of their process to reduce costs. Fuel prices are an almost unswayable factor to be mainly addressed by more efficient aircraft and engines as delivered by ENOVAL. Delivering the engine technologies that will reduce fuel consumption will consequently make the providers more competitive to maintain their position against US competitors (and sometimes partners), who are making similar efforts, and to increase their leadership against newcomers who cannot break the technology barriers set out through decades of continuous investments in Europe.

In terms of financial impact for airline operators, the saving in fuel expected from ENOVAL together with on-going parallel initiatives should lead to significant operating cost reduction. For example, annual fuel for an A320 flying around 3,000 hours, 2 hours each flight, and a gallon at $ 3.50 represents a yearly fuel cost of about $ 10.5m. A reduction of 5% in fuel consumption means a significant saving of more than $ 500.,000 a year, a saving that will increase over the years with an ever-increasing fuel price.

Contributing to the societal acceptance of air transport

Air transport is a basic factor for economic growth and the connectivity required by business, tourism and leisure, as sustainable mobility is essential for Europe's economic development and social well-being. In a globalised economy quick access to even distant locations is a key requirement. This is also reflected in one of the SRIA goals for 2050, namely that 90% of all travellers within Europe should be able by then to complete their journey within 4 hours, door-to-door. Competition brought major changes to air travel - changes that have propelled European mobility forward, successfully helping to bring Europeans closer together, and providing solid foundations for more jobs and a growing economy. The idea of travelling and experiencing new places and cultures has become a reality for many people in Europe during the past 25 years.

This is strongly supported by the decrease of operating costs for airliners, which are often translated into higher frequencies, more routes and cheaper ticket prices. For example, a family trip from Milan to Paris in 1992 would have cost 16 times more than today - the minimum price for one ticket on this route has dropped from more than € 400 to about € 30 today.

As stated above, ENOVAL was addressing the challenge of decreasing operating costs of airliners by reducing fuel burn by 5%, thus indirectly supporting European citizens in affordable travelling,

With increasing air travel the societal acceptance of the impact of transport infrastructure and operations in the neighbourhood of airports needs to be assured. The environmental impact of aviation is being felt most acutely at and around airports, so to provide more capacity, airports have to address the pressure of local population to manage and mitigate the impact of the traffic. Regulators have and will continue to take steps to reduce air transport-indicated emissions (such as Co2, NOx, CO, UHC and Smoke) as well as aircraft noise through the introduction of noise and movement limits. As ENOVAL was addressing the environmental aspects of noise and air quality, it indirectly contributed on the one hand to meet the citizens needs for mobility while on the other hand helped to increase the acceptance of such mobility impacts in local communities in the neighbourhood around airports.

Huge efforts have been made in the past to reduce the noisiness of an individual aircraft at departure and approach, concretely by reducing the Effective Perceived Noise Level (EPNL). EPNL has fallen since modern turbojet and turbofan engines were first introduced – roughly a halving of radiated acoustic energy per decade. This is a remarkable technical achievement – a 95% reduction in the sound power generated by aircraft jet engines since their introduction. With the achievement of the objective of a reduction of engine noise up to -1.3 ENPdB, ENOVAL significantly contributed to the overall development to reduce aircraft noise and to reach the goals of reducing the environmental impact due to noise by -11 dB in 2035.

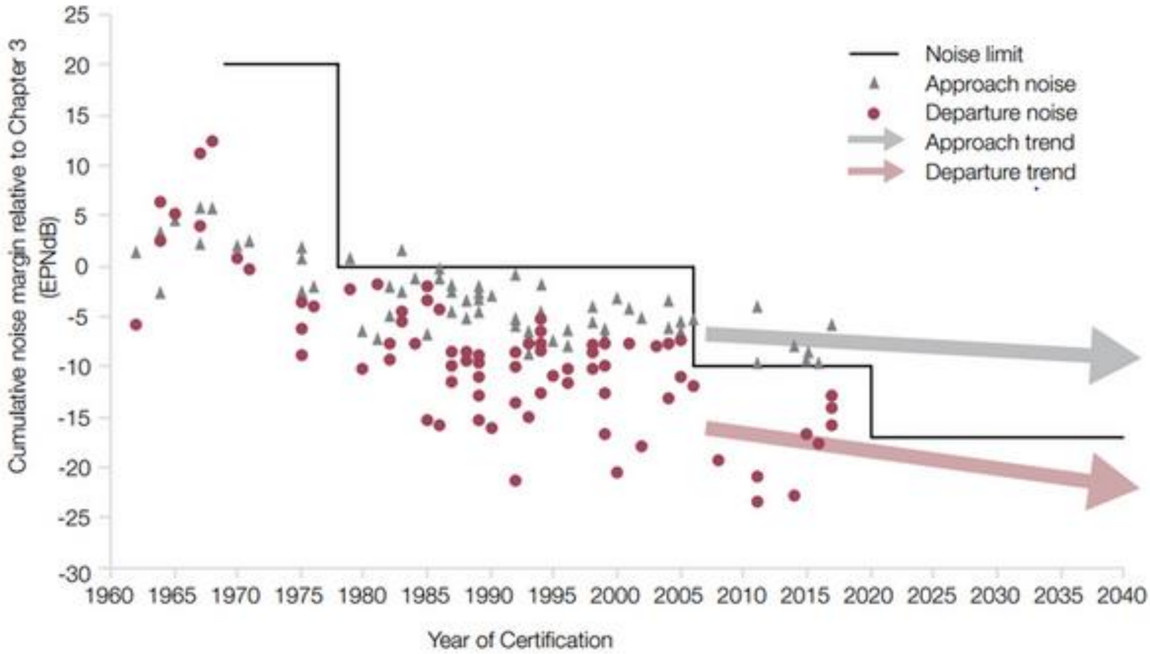


Figure 23 Historic and future trends in cumulative certified aircraft noise levels, including ENOVAL contribution

The ENOVAL results – supported by a broad range of communication and dissemination measures – strongly supported to increase the interest from European policy-makers. Although the reduction of air travel induced impacts is on the political agenda, ENOVAL additionally raised awareness among policy makers with regards to promising solutions for overcoming today's challenges in European aviation. By this, ENOVAL further contributed to setting the agenda in future European research and technology development initiatives, such as Horizon 2020 and the CleanSky programmes.

Supporting European values

ENOVAL has been completed by a multidisciplinary consortium consisting of 35 partners from 11 countries, making the project a success through a truly collaborative approach. Several studies have proven that research has much higher impact when it is concluded collaboratively. ENOVAL has implemented the idea of a connected (research) community during its project lifetime and beyond. Following this idea, ENOVAL was fully in line with the idea of a connected Europe, supporting the exchange and mobility of its citizens. Numerous communication measures as well as open access publications supported the efforts to increase public awareness of the ENOVAL research and thus contributed to the idea of an open and informed European society.

Through the inclusion of the Russian project partner CIAM ENOVAL further helped to transport and promote European values outside its borders. In times of political differences, a fruitful collaboration between institutions from both Europe and Russia constitutes a bright spot and may help to overcome obstacles between these countries.

Finally, it has to be concluded that air transport supports European cohesion and thus the European integration. Being able to travel quickly within Europe (and beyond) makes regions converge. It allows travellers to easily get acquainted to different approaches and ways of living, working and doing things, hence contributing to the successful European integration and cohesion process.

4. List of ENOVAL Publications

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5. The ENOVAL Consortium

The ENOVAL consortium consists of 35 partners from 10 European countries.

Industry (11)

AVIO AERO (AVIO), Italy
GKN Aerospace Sweden AB (GKN), Sweden
ITP Aero (ITP), Spain
MTU Aero Engines AG (MTU), Germany
Rolls Royce Deutschland Ltd & Co KG (RRD), Germany
Rolls Royce plc (RR plc), United Kingdom
SAFRAN Aircraft Engines (SafranAE), France
SAFRAN Aero Boosters (SafranAB), Belgium
SAFRAN Helicopter Engines (SafranHE), France
SAFRAN Nacelles (Safran Nacelles), France
SAFRAN System Aerostructures (Safran SA), France

SMEs (5)

ARTTIC S.A.S. (ARTTIC), France
Centre de Recherche en Aéronautique ASBL (CENAERO), Belgium
Ergon Research SRL (ER), Italy
Global Design Technology SA (GDTech), Belgium
Progesa S.R.L. (PROGESA), Italy

Research Institutes (9)

Bauhaus Luftfahrt e.V. (BHL), Germany
Central Institute of Aviation Motors (CIAM), Russian Federation
Centro de Estudios e Investigaciones Technicas (CEIT), Spain
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Germany
Fundacion Centro de Technologias Aeronauticas (CTA), Spain
Institut Supérieur de l'Aéronautique et de l'Espace (ISAE), France
Office National d'Études et de Recherches Aérospatiales (ONERA), France
Stichting Nationaal Lucht- en Ruimtevaartlaboratorium (NLR), Netherlands
Swerea SICOMP AB (SICOMP), Sweden

Universities (10)

Brandenburgische Technische Universität Cottbus-Senftenberg (BTU), Germany
Chalmers Tekniska Hoegskola AB (CHALMERS), Sweden
École Centrale de Lyon (ECL), France
Mondragon Unibertsitatea (MGEP), Spain
Universidad Politécnica de Madrid (UPM), Spain
Università degli Studi di Firenze (UNIFI), Italy
Universität der Bundeswehr München (UniBwM), Germany
University of Southampton (UoS), United Kingdom
University of Cambridge (UCAM), United Kingdom
Technische Universität Graz (TUG), Austria

ENOVAL consortium, EC Project Officer and Reviewers at the kick-off meeting in Munich, October 2013

ENOVAL partners are located in 10 European countries

6. ENOVAL Project Information

ENOVAL is an initiative of the Engine Industrial Management Group (EIMG).

Project Title:	ENOVAL – Engine Module Validators
Budget:	44.2 m € (EC funding 26.5 m €)
Duration:	58 months, October 2013-July 2018 (incl. a 10-month extension)
Partners:	35 partners from 10 countries
Technical Domain:	Propulsion
Coordinator:	Dr. Edgar Merkl MTU Aero Engines AG Dachauer Straße 665 80995 Munich (Germany)
Website:	www.enoval.eu
Contact:	enoval-info@eurtd.com

Glossary

Abbreviation / acronym	Description
BPR	By-pass Ratio
CA	Consortium Agreement
CAD	Computer Aided Design
CDR	Critical Design Review
CFD	Computer Fluid Dynamics
DDTF	Direct Drive Turbofan
DMU	Digital Mock-up
DoW	Description of Work
EAB	ENOVAL Advisory Board
EB	Executive Board
EC	European Commission
ECM	Engineering Communication Memo
EIMG	Engine Industry Management Group
EIS	Entry into Service
ELLRT	ENOVAL Large Long Range Turbofan
EPNdB	Effective perceived noise level in decibels
EOC	End Of Cruise
ESPI	Electronic Speckle Pattern Interferometry
EU	European Union
FEM	Finite Element Method
FOD	Foreign Object Damage
FPH	Flow Path Hardware
GA	General Assembly
IGV	Inlet guide vane
IMC	Intermediate Case
IMR	Internal Monthly Reporting
IPR	Intellectual Property Rights
IP	Intermediate Pressure
IPS	Inlet Particle Separator
ITC	Inter Turbine Duct
HPT	High Pressure Turbine
LEE	Linearized Euler Equation
LLRT	Large Long Range Turbofan

Abbreviation / acronym	Description
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
LSF	Local Shape Function
NASA	National Aeronautics and Space Administration
OAC	Optimized Acoustic Coupling
OEI	One Engine Inoperative
OGV	Outlet Guide Vane
OPR	overall pressure ratio
PDR	Preliminary Design Review
PGB	Power Gear Box
PM	Person Month
PrADO Program	Preliminary Aircraft Design and Optimization
RTM	Resin Transfer Molding
SDOF	Single Degree of Freedom
S-MT	Small-Medium Turbofan
SFC	Specific Fuel Consumption
SP	Sub Project
SRIA	Strategic Research and Innovation Agenda (for 2020)
SOC	Start Of Cruise
TEC	Turbine Exit Case
TLARs	Top Level Aircraft Requirements
TRL	Technology Readiness Level
UHBR	Ultra High By-pass Ratio
VAFN	Variable Area Fan Nozzle
VL-GTF	Very Large Geared Turbofan
VSV	Vacuum Switching Valve
WP	Work Package