PERSPECTIVES FOR AERONAUTICAL RESEARCH IN EUROPE

PARE

CHAPTER 17

Efficient Propulsion for low noise and emission

Final Report

WWW.PAREPROJECT.EU

Table of Contents

List of Figures

List of Tables

Chapter 17 – Efficient Propulsion for low noise and emission

17.0 Evaluation of research initiatives on the problem of reducing noise level in accordance with the tasks of Flightpath 2050 ACARE

Introduction

Aircraft noise is the most significant reason for the community negative reaction resulted from the aviation transport operation and expanding of airports. So, limiting or reducing of the population suffers from the aviation – generated noise is one of the key ecological goals, and ICAO and Advisory Council for Aeronautical Research in Europe (ACARE) foreground tasks

The noise problem is also conditioned by a significant expansion of aviation transport ranged from 3 to 7 % annually, which will multiply by two and three operating rates by 2030 and 2050, accordingly.

The requirements to the noise level on the ground applied to certification of A/C are described in the "Aviation Noise" Volume I of Addendum 16 to Civil Aviation Convention.

For every category (class) of aircraft, the noise standards are defined in the individual chapters of Addendum 16, Part II. For the main category, the " Subsonic Jet Aircraft" requirements in Chapter 2 are defined for aircraft noise certification for the period ranged from 1971 to 1977 (Ref. Fig. 17.1).

In 1977 Chapter 3 standards reduced by 10 EPNdB as compared with a noise level specified in Chapter 2 in effect till 2006, were introduce

In 2006 Chapter 4 with another reduction of the noise level by 10 EPNdB was introduced. In addition, aircraft noise levels standardized earlier at each point to be certified: at rolling from the side of the runway (under engine takeoff power), at climbing and landing

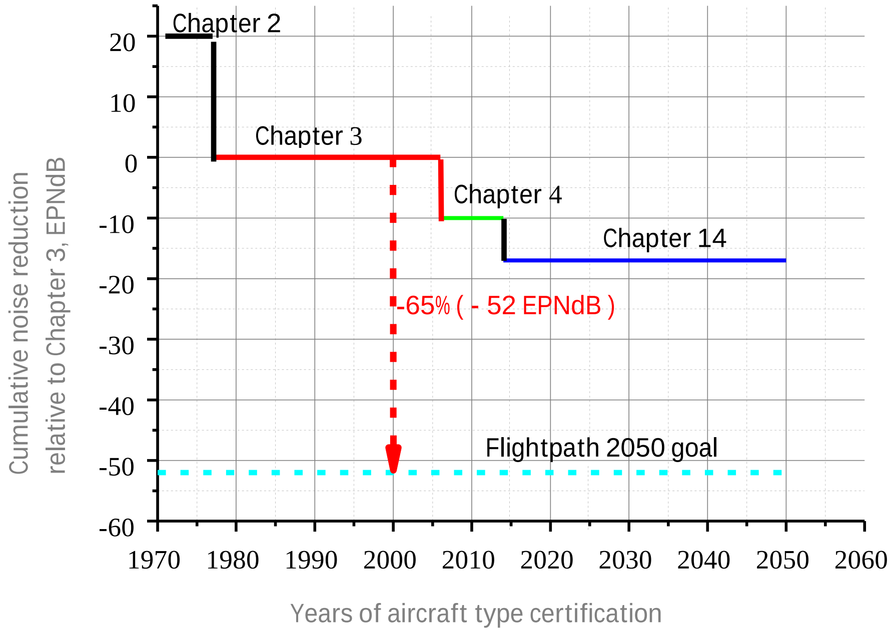

Figure 17.1 - Change in ICAO requirements by years and ACARE goal

With the requirements defined in Chapter 4 brought into effect, the aircraft noise level is standardized by a sum of three certified points i.e. a cumulative level, but in the case of standardized limitations performed in each of three points as defined in Chapter 3.

In 2014 ICAO Council drew a new Chapter 14 noise standard for jet and turboprop aircraft. This updated, more stringent standard is shown in figure1 (together with the preliminary ICAO noise standards for reference) and will be considered the main ICAO standard for noise level of subsonic jet and propfan aircraft for future. This standard applies to aircraft of new types introduced to certification on December 31, 2017 or later, and on December 31, 2020 or later for A/C lower than 55 tons.

Both, ICAO as International organization, and ACARE as Advisory Council for Aeronautical Research in Europe, offer a balanced approach to a control of aviation noise, the main points of which are isolation of noise problem and analysis of various efforts able to reduce PNdB by research of four main trends:

- noise reduction in the source;
- rational planning and land usage management;
- noise reducing operational procedures;
- operational limits.

The goal of these researches consists in defining the actions related to noise taken for obtaining maximum economic ecological advantages.

The Flightpath 2050 ambitious goals are aimed at solving two main problems:

- satisfaction of public needs in safe, more effective and environmentally friendly air transport;
- maintaining global leadership in aviation sector of Europe with competing logistics system.

ACARE issued a Program of Strategic Research & Innovation Agenda (SRIA) with tasks put for aviation industry for the next decades.

SRIA road map includes the following key tasks:

- task No. 1: satisfaction of public and market needs;
- task No. 2: maintaining and expanding industrial production;
- task No. 3: protection of the environment, and energy supply;
- task no. 4: safeguarding;
- task No. 5: research priority, testing abilities and education.

Ways of reduction of engine acoustic emission as one of the main noise sources at takeoff and landing are studied in the context of the Flightpath 2050 ACARE program. These ways are detailed in SRIA task No. 3 and subdivided into tens of subtasks provided with the preliminary deadlines of their fulfilment within 2020 to 2040, and a level of technological readiness.

The present report was drawn for evaluation of research and development trends in the field of aviation perceived noise reduction according to the SRIA task No. 3 on protection of the environment and energy supply, and for achievement of Flightpath 2050 ACARE goal No. 9 on reduction of A/C noise by 65% (-52 EPNdB) as related to 2000 (Ref. Fig. 17.1).

The report summarizes the results of analysis of research of all-European initiatives, national projects and research completed in European countries, as well as research completed out of Europe, which correspond to the goals Flightpath 2050 ACARE program to solve tasks on reduction of acoustic emission.

Problems related to improvement of aero-engine fuel efficiency and reduction of acoustic emission of aircraft are interconnected and considerably as the most vital.

With improved values of fuel efficiency a problem of reduction of harmful substance emissions is partially solved at the same time. It is known that a fan, jet stream and gas generator are the main noise sources in the bypass engines.

In the high bypass engines the fan is the main source of a broadband and discrete noise, but jet stream and gas generator contribute less into a general noise level of the engine.

In turboprop and CROR engines the propeller and counter-rotating propfan are the main sources of noise, accordingly. .

The goal of this research consists in conducting a comparative analysis of the level of technologies achieved in Europe and countries competing in fulfilment of subtasks of SRIA task 3 on reduction of aero engine noise.

The baseline of research methodology comprises analysis and synthesis of the latest technologies and solutions on noise reduction, and also methods of assessment of technological and market commercial readiness of technologies offered within the frames of all-European initiatives, national projects, and also research accomplished in Europe and out of it.

In accordance with SRIA task 3 the first section of the document includes the analysis of all-European and national projects and solutions, research accomplished in countries out of Europe on reduction of acoustic emissions of power plant.

The second section includes the methods of assessment of accomplished research with applying the procedures of assessment of technological and market commercial readiness of technologies for reduction noise level.

The third section includes the results of assessment of technological and market commercial readiness of technologies for 14 projects involving European countries, USA and Russian Federation.

The forth section shows leading SRIA tasks and lagging tasks of European companies, achieved TRL level and time lags (in accordance with the table of SRIA task 3). In addition, countries feasible for a potential cooperation are proposed.

The fifth section describes forecast assessments and recommendations. Technologies able to attain the goals by 2025 through 2030, and those able to attain them by 2050 only are depicted.

17.1. Research of technologies and trends of the noise reduction

Fan, jet stream and gas generator are the basic noise sources in bypass engines [1].

Figure 17.2 shows a typical diagram of trends and qualitative distribution of basic noise sources of GTEs featuring different bypass ratio values.

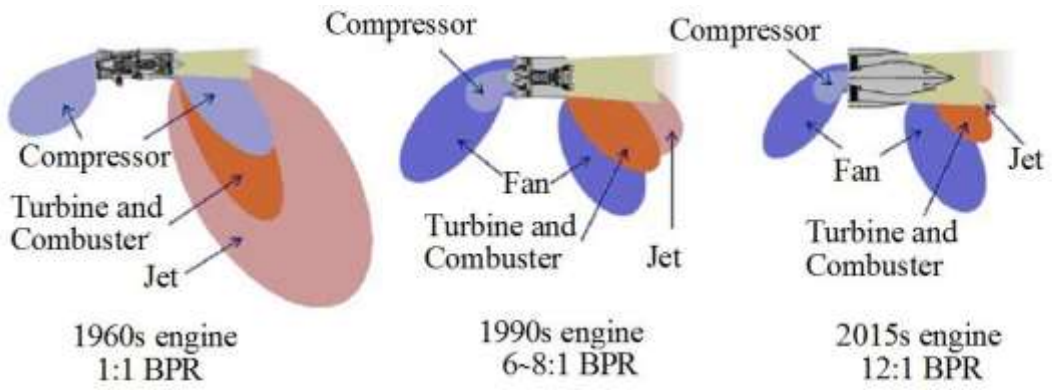

Figure 17.2 - Typical diagram of trend and qualitative distribution of basic noise sources of GTEs featuring different bypass ratio values [1]

Figure 17.3 shows levels of noise pressure for modern GTEs various noise sources specific for takeoff and landing.

Thus, fan is one of the basic sources of broadband and discrete noise, but jet stream and gas generator contribute less into a total noise level of high-bypass turbofan engines.

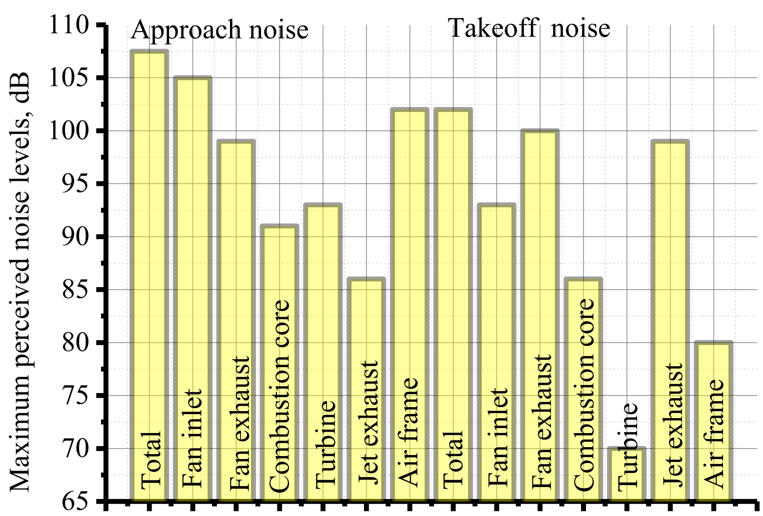

Figure 17.3 - Levels of noise pressure for different noise sources of modern GTEs at takeoff and landing [2]

Propeller is the basic noise source in turboprop engines.

17.1.1. ACARE objective and tasks of Strategic Research & Innovation Agenda on noise reduction of aero engines

The most important objective of ACARE in the Flightpath 2050 program is a significant reduction of atmospheric emissions and noise. This is prescribed in objective No. 9: "In 2050 technologies and procedures available allow a 75% reduction in CO_2 emissions per passenger kilometre and a 90% reduction in NOx emissions.The perceived noise emission of flying aircraft is reduced by 65%. These are relative to the

[https://www.acare4europe.org/sria/flightpath-2050-goals/protecting-environment-and-energy-supply-0]

Required tasks under the Strategic Research and Innovation Agenda (SRIA) CHALLENGE 3. "Protecting the environment and the energy supply", and its subtasks 3.1: "Development of air vehicles of the future: evolutionary steps"; Key element: Propulsion; Breakdown level 1- Reduction of aircraft noise associated with the propulsive system show in table 17.1:

Breakdown level 2 / R&I need	Category	Main activity / to be achieved during	
		2020s	2030s
1. Noise shielding, e.g. acoustic liners and insulation for UHBR ratio engines and high-speed turbines and lean burn combustion systems.	*Technology*	+	
2. Adaptive/active noise control - variable / morphing structures (e.g. fan blades, nozzles).	*Technology*	+	+
3. Low noise propellers design and technology.	*Technology*	+	
4. Low noise fan blade for UHBR engines including open rotor.	*Technology*	+	+
5. Noise reduction technologies for power gearbox systems.	*Technology*	+	+
6. Fixed geometry intake, bypass and exhaust duct optimisation, extension of Treated Area.	*Technology*	+	
7. Develop high fidelity CAA noise modelling capability and integrate into design optimisation capability at system and subsystem level (near and far field).	*Knowledge*	+	

Table 17.1 - Subtasks of CHALLENGE 3 [https://www.acare4europe.org/sria/exec-summary/volume-2]

Revision of projects and research is further represented for SRIA subtasks mentioned above.

17.1.2. Task 1. Protection against noise, e.g., acoustic cover plates/ inserts (SAS) and insulation for UHBR engines (ultra-high bypass ratio engines) and high-speed turbines and systems of lean fuel combustion.

To reduce a level of acoustic emission of power plants the new sound-absorbing materials are researched for use in nacelles and engine itself, for reduction of fan, jet stream and gas generator noise. Use of sound-absorbing structures in nacelles of the next generation engines should attenuate lower frequency levels. It means that sound-absorbing materials should be thicker. At the same time, a nacelle should have thinner walls to save fuel consumption. So, sound-absorbing structures of complicated shapes are considered as a probable solution regarding to absorbing of low-frequency sound with a simultaneous thinning of nacelle panels.

17.1.2.1. All –European projects

Clean Sky consortium fulfilled a research on SFWA project, one of the tasks of this project was the development of SAS (sound-absorbing structures) intended for nacelle leading edge (Advanced Lip Extended Acoustic Panel ALEAP). Within the frames of the project the technology was brought up to TRL 6 in 2010, with Airbus being in the lead in this project [3].

Within the frames of the joint European Large 3-shaft Demonstrator - Aeroengine intake acoustic liner technology development ALTD project the high effective SAS intended for inlet section were developed from 2011 to 2016 with a technology of laser micro perforation applied as a basic one. The technology was studied to TRL 6 [4].

Joint European Smart Acoustic Lining for UHBR Technologies Engines SALUTE project, planned for accomplishment within the period from November 1, 2018 to April 30, 2022 is aimed at the development of SAS for UBPR engines. Specific feature of such SAS consists of their capability to absorb sound at lower frequencies, therefore a nacelle thickness should be thin enough, and this is a factor of significant difficulty in the development. The project authors consider a method of development of arrays of small loudspeakers or passive membranes as a solution to this task. Development study of these technologies to TRL 4 [5] is planned.

In the process of Aeroacoustics Methods for Fan-Noise Prediction and Control FANPAC (1993-1996) project accomplishment, the SAS were developed for use in inlet sections of engines with bypass ratio of 6 to 15, which demonstrated high efficiency (noise reduction by 4 to 10dB) as ranged from 500 to 5000 Hz [6].

The Objective of Integration of a HOT STREAM Liner into the Turbine Exit Casing (TEC) HOSTEL (2012-2014) project consisted in the development of effective SAS intended for a hot section (turbine) of the engine at temperatures of 700°C [7].

17.1.2.2. National projects and research of European countries including associated

Germany. Development of gradient SAS with a smooth variation of porosity and density over a layer thickness is a breakthrough in searching methods of noise reduction. Specific feature of these materials is their high sound-absorbing capability within a very broadband. Technische Universität Braunschweig is involved in Fundamentals of High Lift for Future Civil Aircraft (SFB 880) project on development of special porous sound-absorbing materials [8] offering reduction in acoustic radiation.

France. Safran commenced the development of SAS of complex shapes. Publication [9] describes research of characteristics of sound-absorbing structure (SAS) with 3D spiral cell. The SAS looks like vertical films arranged regularly to secure good mechanical features of panel, and this results in a uniform acoustic behavior over a solid panel (free of combination of various cavity shapes), a cavity cross section is sufficiently small to be compatible with a perforated contour of the acoustic surface the same as in modern airliners.

Numerical calculation of characteristics of SAS under researching was performed by using ACTRAN-TM programming code at the first stage of research. Figure 17.4 shows a 3D model of cell. The cavity shape is a 3D spiral shape entering the parallelepiped with a cross section of a = 25 mm wide, which is close to conventional cells built in modern engine nacelles. The cavity height of b = 32 mm is close to conventional cells built in modern engine nacelles.

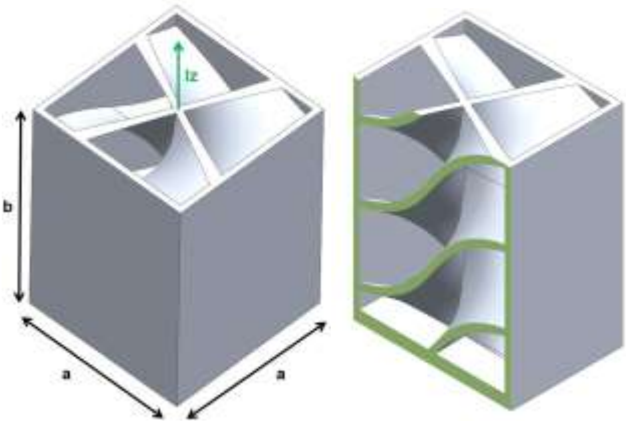

Figure 17.4 - 3D model of SAS cell

Physical experiment was conducted in NLR acoustic wind tunnel at the next stage of research. Figures 17.5 to 17.7 show the models under researching. The results were compared with those obtained at numerical modelling in ACTRAN-TM. The researches show that a behavior of the 3D spiral-shaped panel of 32 mm in thickness is the same as of a conventional SDOF (Single Degree Of Freedom) cell of 50 mm thick. By other words, the same acoustic characteristics can be obtained by using 3D spiral cavities, but with a cell thickness reduced by 36%.

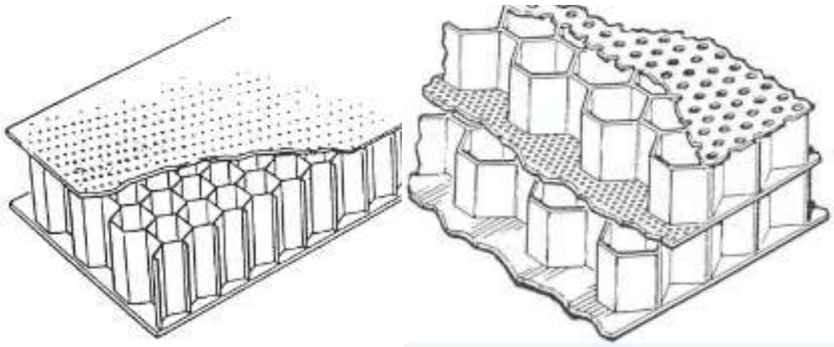

Figure 17.5 - Structure of SDOF cells (at the left) and DDOF cells (at the right)

(Single Degree Of Freedom (SDOF), Double Degree Of Freedom (DDOF))

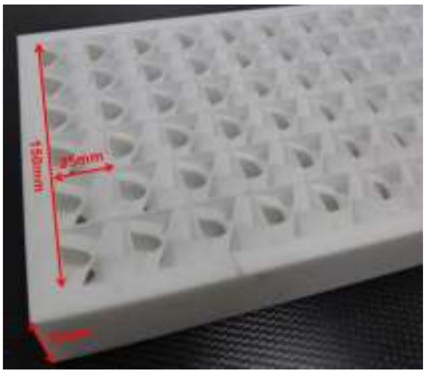

Figure 17.6 - Research panel prior to bonding

Figure 17.7 - SDOF SAS panel of 50mm in thickness

Manufacture of 3D acoustic panel is a main difficulty in construction of 3D spiral-shaped cavity. In reality it is limited by a 3D stamping and, thus by small part of nacelle. Thus, further activity of Safran Nacelles is focused on identification of industrial solution for large acoustic panels with addressing to low frequencies at low thickness [9].

17.1.2.3. Projects and research performed countries out of Europe

Russian Federation. CAGI is involved in the "Development of methods of reduction of A/C acoustic effects on environment with accounting azimuth lack of uniformity of sound-adsorbing panels (SAS) arranged in air-intake duct, amplitude and tendencies of sound rotating modes varied at a flow in leakage" project conducted within the frames of the Federal target program titled "Research and developments on priority trends of Russian science and technological complex development for a period from 2014 to 2020".

During fulfilment of the project the following results exceeding the world levels were obtained [10]:

- development of theoretical method of accounting axial joints of lining impedance in cylindrical and rectangular channels;
- development of analytical model of impact of SAS uniformity absence on propagation of rotating modes in the cylindrical channel as based on the method of secular equations and singular perturbation theory;
- experimental confirmation, in anechoic chamber of AK-2, of effect of essential dependence of tendency diagram of sound radiation from air intake section on a speed mode for suction and wake flows;
- development of method of high-precision adjustment of engine noise generation system in channel, which allows to implement various azimuth modes with azimuth numbers defined in advance for cases when a dynamics with various gain-phase characteristics are used;

- - development of a computer program for defining a modal composition of a sound field in the channel with a flow in the process of generation of a small number of correlated dominating azimuth harmonics;
- test of methods of research of non-axis-symmetrical SAS effectiveness conducted in anechoic chamber by using a full-scale model of air intake with extraction of a sound field modal structure.

Research on development of combined turbine noise suppressors and defining a proper area for installation them are conducted purposely for noise reduction. The results obtained during research [11] show that a latticed suppressor (fig 17.8) is a broadband and universal unit reducing all components of noise within a whole band of frequencies approximately higher than 1.0 kHz. In average, reduction of sound power for four-five noise components is nearly 4dB, i.e. doubled value.

Figure 17.8 - View of latticed suppressor in flowpath section of stage C179-1

High-temperature noise suppressors (composite sound-absorbing structures), a lining of nacelle mixing chamber [12] are used for provision of acoustic effectiveness in the main duct.

The advanced method of noise reduction in turbine is an acoustic lining of its flow path section over a rotor wheel [12]. The method effectiveness was tested by using a fan [11].

USA. NASA developed the effective SAS of low weight (made of oxide/oxide ceramic matrix composite (CMC)), which withstand high temperature (up to 1000 ºC) and feature a wide absorbing band, SAS cells have a variable depth [13].

17.1.3. Task 2. Adaptive/active control of noise, variable /varying structures (e.g. fan blades, nozzles)

Acoustic and aerodynamic improvement in future will be based on a boundary layer control. Active boundary layer control, i.e., blowout of extra air mass into aerodynamic trace, offers a reduction of a broadband noise. In addition, it is possible to research the application of a combined use of passive and active boundary layer controls in elements of fan and straightener blades.

17.1.3.1. All –European projects

Within a scope of Adaptive and Passive Flow Control for Fan Broadband Noise Reduction FLOCON (2008-2012) project four TRL4 technologies were developed for reduction of a broadband noise in fans: corrugated leading and trailing edges, installation of a miniflap in fan blades, flattening of aerodynamic trace by using blowup method [14].

In the Design of innovative CROR blade and pylon DINNO-CROR (2010-2012) project two methods of noise reduction over CROR blades were researched: the active method of trace reduction beyond the first raw of blades by using a dielectric barrier discharge (DBD), and porous surface of blades. Results of the research showed that porosity should exceed 25%, thus, it causes aerodynamic loading on blades. It was confirmed that DBD technology is of a very low potential for attenuation of a tonal noise in a real CROR configuration, so, such researches were stopped. From the research it was revealed that a noise trend for CROR tones from a front raw of blades depends significantly on a presence of pylon, at the same time, a level of sound pressure is increased significantly in the front semi-sphere [15].

17.1.3.2. National projects and research of European countries including associated

Results of ONERA research demonstrated the effectiveness of a boundary layer active control used in blades of axial-flow fans and compressors. Active effect produced on a boundary layer results in a reduced aerodynamic trace beyond a blade, and contributes to a reduction of a broadband noise, but a discrete noise can increase simultaneously [16].

Great Britain. The results represented in the publication [17] show the effectiveness of active methods of boundary layer control application.

Effects of active methods of flow control (boundary layer blow out and suction) made on acoustic and aerodynamic characteristics were experimentally researched and described in Publication [17]. A plate was used as a research object.

It is noted that reduction in a broadband noise and coherent structures beyond the plate are possible with applying the control rational parameters. Active flow control results in an increased speed and pressure beyond the plate.

Italy. Evaluation of fan blades with Shape Memory Alloys is represented in publications [18, 19] as performed by using a physical experiment and numerical modelling of aerodynamic loads. The research results demonstrate that Shape Memory Alloys allow to obtain high aerodynamic characteristics of blades within a wide operational range.

Germany. Authors of publication [20] revealed the possibilities of modification of a material structure of the adaptive compressor (fan) blade by applying a physical experiment with the model. The effect of modifying a material structure of the adaptive compressor blade will allow to increase aerodynamic and aero-elastic features of blades, and, as the result, to improve acoustic characteristics.

Authors of publication [21] demonstrated the effectiveness of reducing the first harmonics by 21.4 dB by using an optimized blow system, which allowed to make effects not only on filling of trace but on vortex structures at the hub and in a blade periphery section as well.

17.1.3.3. Projects and research out of Europe

Russian Federation. Advanced methods of jet stream noise reduction are under researching in Russia as the research programs.

Activities on research of active control of jet stream acoustic characteristics are conducted with using micro-jets. The results obtained during the research showed that the integration of active control of jet stream noise with use of chevron nozzles allows to reduce a level of jet stream sound pressure [22].

Liquid injection, use of skewed nozzle, micro-jets, high-frequency excitation are considered as the methods mentioned above. All these methods feature a potentiality for noise reduction by 1 to 2 EPN dB at takeoff running and climbing [23, 12].

USA. Nacelles with the inlet free of joints and chevron nozzle made of Shape Memory Alloys were developed within a scope of Quiet Technologies Demonstrator 2 program. Application of the developed technology allows to reduce noise level by ~ 3–4 dB at takeoff, and save fuel consumption by -1%, implementation of technologies was accomplished in B777 powered by GE90 engine [24].

To reduce noise level, the application of active noise control system containing acoustic resonators mounted on the fan outlet guide vanes and the MEMS technology - based units allow to reduce noise level in source by ~ 50-–60% [24].

Within the scope of Quiet Aircraft Technology (QAT) Program *(since 2001)* "revolutionary" technologies for the next generation of multi-role A/C engines with a wide range of flight velocities were developed. The program was focused on research of power plants for passenger aircraft. As the result, reduction of noise level by -20 EPN dB in relation to ICAO Chapter 3 norms was achieved.

The following technologies were researched within the frames of this program [25, 26]:

- active control of boundary layer on fan blades (blow out of extra air mass through the edge of rotor wheel);
- installation of acoustic above-rotor facilities. The acoustic above-rotor facility is installed over the fan rotor wheel blades, which prevents noise propagation both upstream and downstream. Test results show that such concept provides noise level reduction by ~ 3–4 dB;
- installation of splitter in a passage beyond the fan. This method allows to reduce noise level downstream beyond the fan stage due to installation of additional acoustic surface;
- The main factor in this method is minimizing of total pressure losses in the bypass duct resulted from additional strength. Results of research of one of the variants of such method conducted in a wind tunnel showed, that when a type and location of splitter are defined in a proper way, then noise level can be reduced by ~ 1.5 dB, but, at the same time, losses in thrust generated by bypass flow can be of -1%;
- installation of Gelmgolts resonators ("soft" straightener blades). This concept consists in provision of cavities with installed Gelmgolts resonators in them on the straightener blades, which suppress pressure oscillations over blade surfaces. Results of researching a model of a low-frequency fan showed that reduction of noise level within a wide frequency range can be up to ~ 1.5 dB.

Japan. Within a scope of ECAT - Environment-Conscious Aircraft Technology Program, (part of Green engine technology) project, special JAXA and IHI chevron nozzles are developed, they allow to reduce acoustic radiation from the engine jet stream, an increase in bypass ratio and, accordingly, in fan diameter are provided for [27].

Ukraine. Authors of publication [28] showed that use of passive control of boundary layer over fan blades (bi-rotating fan) allows to reduce acoustic radiation of fan due to redistribution of aerodynamic load and reduction of losses in the boundary layer at flowing around.

17.1.4. Task 3. Design and technologies of quiet propellers

17.1.4.1. All-European projects

Clean Sky 2 consortium, within the frames of implementation of platform tasks of the integrated demonstrator of engine technologies (Engines ITD) (demonstrator «Business aviation/ Short range regional Turboprop Demonstrator, 2015-2020»), Safran Helicopter Engines company coordinates the development and integration of new quiet propeller for the Integrated Power Plant System (IPPS) [29].

All-European Study of Noise and Aerodynamics of Advanced Propellers SNAAP (1993 to1996) project was aimed at the development of a program code for forecasting aerodynamic and aeroacoustic characteristics of propellers, and also the development of propellers with sweep blades, which offered improved acoustic characteristics for turboprop engines [30].

Within the frames of Innovative design of hubs and propellers IDOHAP (2010-2011) project a key technology of CROR model design was developed for testing in the wind tunnel, the first stage had 11 blades, and the second 9 blades [31].

17.1.4.2. National projects of European countries including associated

Great Britain In publication [32] revisions of acoustic emission sources in far and near acoustic fields are given. A critical analysis of methods of forecasting acoustic radiation in far and near acoustic fields is described.

Germany. It is shown In publication [33] that with decrease of a diameter of transonic propeller at a continuous rotational speed a significant noise reduction can be achieved. But, in this case, a number of blades should be increased. In addition, authors note that effective aerodynamic airfoils should be used for propeller blades.

Italy. Publication [34] represents the results of the analysis of a dynamic control system intended for improvement of attenuation of a noise transmitted from the propeller to the A/C fuselage. Within the research scope the companies SFIDA, UNINA and NOVOTECH joined forces with LEONARDO - FINMECCANICA - AIRCRAFT DIVISION in order to design an advanced device for noise control, which will be installed on a turboprop aircraft of new generation [34].

17.1.4.3. Research in countries out of Europe

Russian Federation. CAGI is involved in scientific support of A/C at different stages of its development and experimental operation in order to provide the assigned level of perceived noise and noise in passenger cabins. The institute conducts research on revision of a noise generation mechanism, and modelling of aviation noise sources (vortexes, jets, and aircraft and helicopter propellers, airframe elements) [35]

In 2011 the specialists of CAGI aerodynamics department carried out the next series of tests of a schematized aircraft fuselage model represented in a form of a rotary body equipped with a propeller at its tail end section. The scientists revealed a presence of a positive aerodynamic interference, which is exhibited as a reduction of a required power on the pusher propeller shaft for development of thrust, which equilibrates a drag of the rotary body arranged in front of the propeller. A/C fuel consumption can be decreased by 8 to 10 % due to a reduction of required power of a power plant [36].

The results of experimental tests of acoustic radiation in power plants with propellers are described in publications [37 to 40].

Publication [37] includes the results of the experimental-calculation research of effects of a number of blades and diameter made on a noise of propeller operated at Re numbers higher than 10^6. It is shown that increased number of blades with maintained geometrical and aerodynamically similarity of propellers, and also a permanent Mach number of peripheral velocity, result in a significant reduction of noise caused by aerodynamic load. At the same time, a displacement noise and a broadband noise are slightly increase.

Experimental data on propagation of acoustic radiation of piston power plants installed in A/C are summarized in publication [38]. Factors of propagation of a total acoustic radiation of a power plant and its separate elements, which can be used in calculations of a noise generated by light airplanes and small-sized UAVs in-situ were obtained. Publication [39] describes the basic results obtained during the experimental research of acoustic characteristics of An-2 power plant under static conditions. Energy, spatial and spectral characteristics of acoustic radiation of a power plant were obtained. The authors established that a basic share of the power plant acoustic radiation energy is concentrated at the area of low frequencies (16 to 100 Hz). In this frequency area a maximum spectral density corresponds to a radiation at frequencies multiple to a passing frequency of propeller blades, and also to frequencies multiple to repetition frequencies of sparks in the engine cylinders. Propeller and engine are considered as a source of a low-frequency (up to 500 Hz) component of a broadband radiation. Vortex sheet with propeller is a dominating source of a broadband high-frequency component. Share of high-frequency broadband acoustic radiation (1000 to 5000 Hz) in a total acoustic power of power plant is not higher than 1%.

The basic results of experimental research of acoustic characteristics of light propeller airplane of Yak-18T type under static conditions are represented in publication [40]. Spatio-terminal, spectral and energy characteristics of acoustic radiation of power plant are described. Results of research allowed to isolate a new mechanism of generation of pulse-type acoustic radiation from subsonic propeller. Authors established that acoustic power of a power plant is defined by a power of a total acoustic radiation from propeller and engine.

USA. Authors of publication [41] presented the results of inlet turbulence effects made on a total level of noise of propeller with four blades at a rotational speed of 3000 rpm. It is shown that with increasing a level of inlet turbulence by 1% a broadband component of noise increases by 2 dB. Detailed analysis of sources of noise generated by engines of different types including turboprops is described in publication [42]. The author developed the measures for a further acoustic improvement of single-row and two-rotor propellers. For recent years a specific attention was paid to application of technologies of electrojet engine in the aircraft design. Electrojet system characteristics open such new spheres in aircraft design as use of a distributed electrojet engine (DEP). Such approach allows to install electrojet engines at various areas in order to achieve higher effectiveness due to integration of engine unit with airframe. Within the frames of SCEPTOR project, NASA develops an A/C demonstrator with a great number of "propellers of high-lifting capacity" distributed over a leading edge of wing, and two "cruising" propellers (per one on each wing). Propellers of high- lifting capacity operate at low flight velocities (flight conditions at takeoff/approach). In the publication the acoustic characteristics of all propellers are evaluated by using the methods of numerical modelling [43].

China. Authors of publication [44] showed that a blade shape is very important for acoustic improvement of propellers. Results of numerical and physical experiments of propeller acoustic characteristics are represented in this publication.

Publication [45] describes research of mechanism of acoustic noise generation at rotation of eight-blade propeller with account of inlet nonuniformity of flow.

Canada. In turboprop engine a problem of noise reduction arises primarily as connected with a propeller noise reduction. Propeller noise reduction is based on change of number of blades, optimization of blade shape, use of active system of noise reduction [46].

17.1.5. Task 4. Quiet fan blade for UHBR engines including CROR open rotor

17.1.5.1. All-European projects

In the integrated Clean Sky 1 program the researches were conducted within a scope of Sustainable and Green Engines (SAGE) ITD platform, in subprogram of development of technologies No.3 (SAGE 3) - Advanced Low Pressure System (ALPS) aimed at the development of a composite fan blade made of CTi (Carbon Titanium) for advanced and ultra-fan engines, the developed fan blade allowed to reduce noise in the range from 1 to 3 EPNdB , in Clean Sky 1 this technology was brought to TRL6 with Rolls-Royce being in the lead [47].

Within the frames of Clean Sky 2 program and tasks of Engines ITD platform, a demonstrator of engine with ultra-high propulsive efficiency for short/medium range «Ultra-High Propulsive Efficiency (UHPE) demonstrator addressing Short / Medium Range aircraft market, 2014-2023») is under development, Safran Aircraft Engines company is responsible for design, development and ground tests of the engine unit demonstrator for verifying low pressure modules including a fan, which are required for start of engine with ultra-high bypass ratio ranged from 15 to 20. It is planned to bring the fan technologies under development to TRL 5-6 by 2022 [29].

In Clean Sky 2 program, one of the tasks in Engines ITD (demonstrator «Very High Bypass Ratio (VHBR) Large Turbofan demonstrator, 2014-2021» and «Very High Bypass Ratio (VHBR) Middle of Market Turbofan technology, 2014-2021») platform consists in development, ground and flight tests of engine equipped with a new fan featuring a low noise level [29].

Main tasks of validation of improved turbomachinery noise prediction models and development of novel design methods for fan stages with reduced broadband noise titled as TurboNoiseBB (2016-2020) project include the development of experimental base and method for forecasting a broadband noise of fans, development of fans with low level of acoustic radiation by using the developed method [48].

Within the scope of Engine Module Validators - ENOVAL (2013-2018) project a fan of the engine with bypass ratio of up to 20 was developed. Novel design features of low-pressure fan (optimization of blade shape, number of blades, weight) made it possible to reduce noise level up to 1.3 EPNdB and totally to 9 EPNdB, the technologies were developed to TRL 5. Start of engines with implemented developed technologies is planned for 2025-2030 [49].

Within the frames of European VITAL program incorporating 53 participants (from 2005 to 2010) the researches in the field of noise reduction of bi-rotating and directly geared fans of classical layout were conducted. As the result of a program performed with the engine with bi-rotating fan (Snecma as a leading executor) a model of fan was developed, passed aerodynamic and acoustic tests which demonstrated possibility to increase its efficiency by -1–2% and reduce noise level by -3.5–4%. For GTEs with directly geared fans (traditional layout) Rolls-Royce Company developed and tested fan models. As a result, the defined goals were achieved: reduction of fan noise level by~6 EPN дБ; increase of fan efficiency by 2%; and fan weight reduced by -30% [50]. Results of optimization of number of blades of a stage of one of the bi-rotating fans (open rotor) developed according to VITAL program, are given in publication [51].

Rolls-Royce Company headed a validation of Radical Engine Architecture systems - DREAM (2008-2012) project, which included 47 partners from 13 countries, it introduced the best expert information and possibilities of EC and Russia aviation industry. As the result of DREAM project the technologies were developed to TRL 4-5. One of the tasks was the development of engine architecture with CROR, one of the basic problems consisted in noise reduction in such engines [52].

Within a scope of Experimental and Numerical Investigation of Turbulent Boundary Layer Effects on Noise Propagation in High Speed Conditions - ENITEP (2012-2016) project the mechanisms of CROR integration with fuselage within the range of Mach numbers from 0.4 to 0.78 were researched in order to reduce CROR engine noise [53].

Within a scope of the integrated Clean Sky 1 program in a subprogram of development of technology demonstrator No. 2 (SAGE 2) the Counter-Rotating Open Rotor (CROR) component was researched, the researches continued further in Clean Sky 2. In 2017 SAGE 2 CROR demonstrated novel technologies including propeller blades, propeller pitch governor system, reduction gear with counter-rotating two- rotor propeller, and acoustic optimization on the Safran test bench. This full-scale demonstration confirmed a technical feasibility of CROR, expectations of significant save in fuel consumption (-30% as compared with that in 2000) and capability to satisfy effective ICAO Chapter 14 requirements related to noise [47].

17.1.5.2. National projects and research of European countries including associated

The results of activities performed in the NUMECA [54] module program allow to estimate a mechanism of generation of acoustic radiation from open rotor. Studies were conducted by using a numerical experiment with use of NLH (Linear Harmonic method). The first and the second blade rings had 9 and 12 blades, correspondingly, peripheral radius was 2.5 m, hub radius was 0.75 m, rotational speed of the first blade ring was 783.8 rpm, rotational speed of the second blade ring was 763.8rpm. Figure 17.9 shows 3D model of open rotor under researching.

Figure 17.9 - 3D model of open rotor under researching

Great Britain. Rolls Royce Company ensures noise reduction of fan by using an improved low-speed fan (reduction of dipole acoustic noise source), the wide-span fan blades are twisted over their height and are made of composite materials.

Reduction in acoustic interaction between a fan rotor wheel and blades is provided by inclined and specially profiled blades, with a number of blades chosen for ensuring “shutoff” effect.

Development of optimized straightener blades allowed to reduce discrete and broadband noise significantly.

To achieve this goal a comprehensive aerodynamic and acoustic optimizations of the fan straightener blades were completed, number of blades was decreased, the variants of reduction of blade number from 42 to 14 units were considered [55].

Germany. Results represented in publication [56] showed that with decreasing a diameter of the second rotor wheel of the open rotor by 20%, an acoustic emission resulted from interaction between the first and the second rotor wheels reduces.

Great Britain. Leading engine-manufacturers apply composite materials to blades of new generation engines as featuring high strength properties, low weight, which allow to develop fans for bypass engines of high bypass ratio with a diameter higher than 1.5 m, due to their low weight and sufficient strength of blades. An example of new materials offering a significant improvement of acoustic characteristics is a material developed recently, which simulates a structure of an owl's wing. This material was developed by the researchers from the Cambridge University. The tests of a model specially manufactured by using 3D technologies demonstrated a noise reduction by 10 dB without any noticeable effect made on aerodynamics [57].

17.1.5.3. Projects and research in countries out of Europe

Russian Federation. Evaluation of noise of the A/C powered by two open- rotor counter-rotating engines is described in CAGI publication [58]. Open rotor, by its design, consists of two rotor wheels rotating in opposite directions.

The results represented in publication [59] showed that peaks of tonal noise at combinative frequencies in a low-frequency section of spectrum are added to the traditional noise components in the open rotor noise spectrum. This complicates reduction of a perceived noise for the A/C powered by such engines.

Research studies on the development of methods for reduction of fan noise are aimed at a further improvement of methods, which are currently at the level of technological readiness (the engine demonstrator passed the tests), for a medium-term outlook. The basic of these methods are the methods of changing of sweep of rotor wheel (RW) blades, sweep and inclination of straightener (SB) blades and transition to an ultra-bypass ratio [12]. It was concluded that these methods will offer reduction in a fan tonal noise and a broadband noise by 2 to 4 dB and 1 to 3 dB, accordingly, as based on the results obtained in studies. At the same time, it is expected that effects of sweep and inclination of straightener blades made on a tonal noise radiated into a rear semi-sphere will be ranged from 3 to 5 dB.

Inclination of straightener blades is considered as an advanced method offering a reduction of fan acoustic emission. Publication [60] describes a comparative analysis made with the following three variants of straightener blades: without inclination, with 30° inclination in the direction of rotation, with 30° inclination in the direction opposite to rotation (figs.17.10 to 17.13).

Figure 17.10 - Straightener blades without inclination

Figure 17.11 - Straightener blades with 30° inclination in the direction of rotation

Figure 17.12 - 30° inclination in the direction opposite to rotation

Figure 17.13 - Fan

Researches were completed by using 3DAS program and compared with the results obtained during experimental studies obtained with C-3A model in CIAM (fig. 17.14).

Figure 17.14 - Scheme of acoustic laboratory during research of acoustic characteristics

It was shown that a stage with straightener blades inclined in the direction of rotation makes possible to reduce acoustic radiation on the harmonics of interaction between the rotor and stator. Evaluation of effectiveness of a computational method by using 3DAS program showed that the results obtained by a calculation are tending to a change in acoustic characteristics, but inaccuracy is sufficiently high. Authors explain this inaccuracy by the effects made by stands during a full-scale experiment not accounted in calculations.

USA. Analysis of performance of engine with open rotor is described in publication [61] for a wide range of operational power settings. Comparison of engines is shown in figure 17.15.

Calculation of performance of engine with open rotor is given in NASA publication [62]. It is shown that a designed engine will feature higher cost effectiveness, in addition, it is noted that such engines are provided with a reserve of 13dB in accordance with ICAO Chapter 4 requirements.

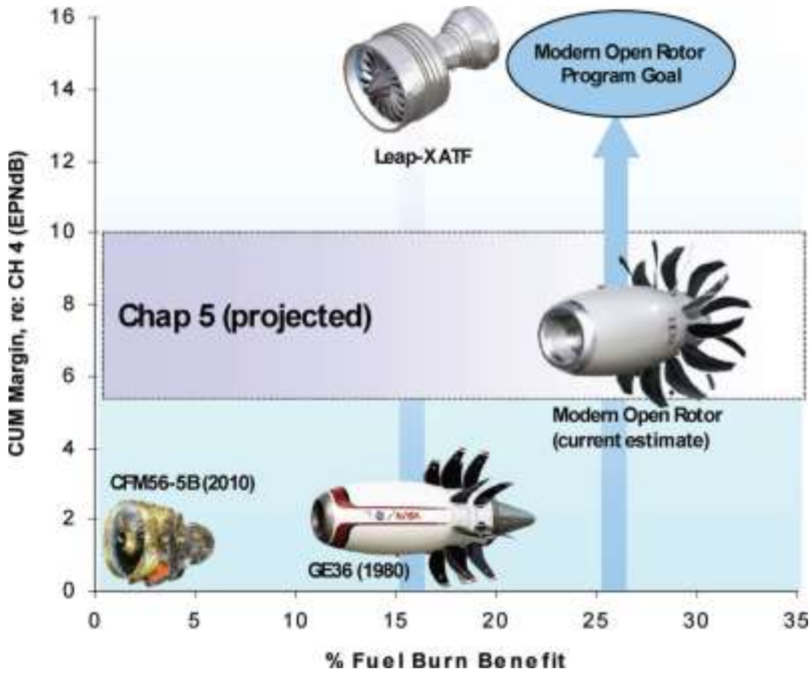

Figure 17.15 - Advantages of engine with open rotor

The results of NASA studies [63] show that for reducing acoustic radiation it is necessary to lower a trace beyond the first rotor, and decrease an affect caused by vortexes beyond the second rotor separated from the blade tips.

General Electric (GE Aviation) is involved in development of GEnx engine family. The GEnx engine family offers a new level of operational effectiveness due to a fan casing and blades made of polymeric composite material, and also a unique TAPS combustion chamber, whose emission levels, fuel consumption saving, ignition and life are the second to none. Optimized design of fan blades without platforms supports a reduction of vortex noise and decrease of fan acoustic emission level [64].

Japan. Japan Aerospace Exploration Agency develops a quiet fan [65], a blade shape is simultaneously optimized due to improvement of aerodynamics and acoustics.

17.1.6. Task 5. Noise-suppression technology for reduction gears

Increase of GTE bypass ratio up to 50 to 60 (Open Rotor) requires a compulsory using of a reduction gear. From one side, the reduction gear reduces rotational speed resulting in reduction of dipole and quadrupole component of noise, from the other side, it increases weight and is an extra source of mechanical noise, but use of composite materials reduces substantially weight, and application of 3D designing and 3D stamping of the reduction gear elements offer an appreciable reduction of probable mechanical noise. Thus, the projects regarding to research of optimum designs of fan reduction gear are vital.

17.1.6.1. All-European projects

A number of technologies of evaluation of aeroacoustic characteristics for a concept of potential reduction of noise of reduction gear and transmission of a regional aircraft were researched within the frames of Clean Sky GRA "Low-Noise Configuration" program [66].

Activities on development of a light-weight modified reduction gear featuring the improved acoustic characteristics were accomplished in the Clean Sky project subprogram of technological demonstrator No.4 (SAGE4) [47].

In Clean Sky 2, ITD project on development of "Business aviation/Short range regional Turboprop Demonstrator, 2015-2020" demonstrator, a subdivision of Safran Helicopter Engines company coordinates the development and integration of reduction gear for Integrated Power Plant System (IPPS) [29].

Within a scope of Clean Sky 2, Engines ITD project, one of the tasks in projects on development of a Very High Bypass Ratio (VHBR) Large Turbofan demonstrator (2014-2021 гг) and Very High Bypass Ratio (VHBR) Middle of Market Turbofan technology (2014-2021 гг) demonstrators is a development, ground and flight tests of the engine equipped with a new fan reduction gear, which will feature low noise level [29].

Within the frames of Geared Turbofan Test Rig - GTFTR (2013-2016) project an epicyclic Power Gearbox (PGB) titled as Integral Drive System (IDS) was developed [67].

The next phase of IDS development was High load gear and bearings materials - HILOGEAR (2017-2020) project, within a scope of new materials for supporting optimum operation of IDS reduction gear, and bearings as well, will be developed [68].

Design of Experiments to OPTIMIZE design solutions for a Power reduction Gearbox - OPTIMIZE (2014-2016) project regarded to the optimization of a reduction gear design with an objective function of improvement of reliability, reduction of noise, improvement of portability and weight reduction [69].

Decreased fan speed in Ultrafan engine will be supported by use of a special reduction gear. Technology of a fan reduction drive is considered a rather attractive solution of problem of weight reduction. Use of reduction gear will offer a reduced fan rotational speed, which makes a beneficial effect on reducing a noise caused by fan rotation. Use of composite materials allows to decrease weight of fan blades [70].

17.1.6.2. Projects and research out of Europe

Russian Federation. Tooth gears used in aero engines and helicopters are of a supreme importance in the GTE engine development industry. High-speed reduction gears are the most important elements of high bypass ratio aero engines of next generation. A reliable operation of reduction gear and entire engine is in a direct dependence on reliable tooth gears. CIAM is concerned with such problems of reduction gear reliability as: elimination of vibrations resulting in deterioration of teeth stiffness, use of updated tooth gears for increasing reliability to reduction gears, noise reduction, transition of components to on condition maintenance and a number of other problems. Put into service of modern tools of monitoring and diagnosis of reduction gear and transmission behavior are of a supreme vitality today [71].

USA. Pratt&Whitney PurePower PW1000G engine is designed in order to improve all operational data: fuel consumption, contamination level, noise and maintenance cost that will make possible to save maintenance costs to the maximum.

Noise reduction in PW1000G engine is supported by using a fan drive system, which allows to rotate engine fan with a lower speed as compared with LPC and turbine, while increasing bypass ratio. This technology ensures much lower fuel consumption and levels of generated contamination and noise [72].

17.1.7. Task 6. Optimization of fixed geometry of inlet section, bypass channel and outlet section, expansion zone

17.1.7.1. All-European projects

Within the frames of Efficient Shape Optimization of Intake and Exhaust of a Tiltrotor Nacelle - TILTOP (2010-2011) project a procedure of optimization of nacelle inlet and outlet sections of aero engine is developed [73].

In the Innovative counter rotating fan system for high bypass ratio aircraft engine - COBRA (2013-2017) project CIAM (Russia) is one of the partners, the increase of bypass ratio up to 15 to 25 for bypass engines with low-pressure fan was studied as based on the results of VITAL project [74].

17.1.7.2. National projects and research of European countries including associated

Germany. Publication [75] represents the results of experimental studies of acoustic characteristics of A320 auxiliary power plant with different suppressors (fig. 17.16). It is shown that use of suppressors makes possible to reduce a level sound pressure by 20dB. Among the researched suppressors the authors focus their attention on a new PFW Aerospace AG suppressor featuring high characteristics within a wide frequency band.

Figure 17.16 - A320 auxiliary power plant

17.1.7.3. Projects and research in countries out of Europe

Russian Federation. Use of chevron or splined facilities for nozzles of internal and external channels is the method of reduction of jet stream noise for engines with m=7 to 9 for a medium-term outlook. Effectiveness of this method is 0.5 EPN dB at takeoff (an average mean value of certification values at takeoff running and climbing) [76].

The effective method of reduction of a jet stream noise is an increase of a bypass ratio.

In accordance with the approximate evaluations, while using the 3dB/m dependence, the power plant with a bypass ratio of m≈12 will reduce A/C noisiness in checkpoints by 9 EPN dB [76].

Table 17.2 represents methods of jet stream noise reduction for medium-term outlook.

Method	Evaluation of noise reduction	Main problems of integration
Chevrons of fixed geometry	1-4 EPN dB at takeoff running and climbing	Integration of nacelle/pylon for reduction of fuel consumption
Chevrons of variable geometry	0.5-1.0 EPN dB at takeoff running and climbing	Reliability, easiness of maintenance and production
Geared GTE of high bypass ratio of , m>10	Depends on operational power setting	Engine weight, nacelle drag; operational characteristics
Long-length channel with forced mixing of flows	1 to 2 EPN dB at takeoff running and climbing	Applied to nacelles with long-length fairing and m ≈4 to 6

Table 17. 2 - Methods of jet stream noise reduction for medium-term outlook [76].

Comparative analysis of methods used for exhaust jet noise reduction in aero engines is described in publication [76]. It is shown that mixing of streams is the only method of improvement of engine acoustic characteristics without decreasing its cost-effectiveness.

With high values of bypass ratio (m>6 to 8) a positive efficiency effect obtained due to mixing is not significant and does not justify the increased weight of engine at the cost of mixing chamber, at the same time, an acoustic effect is kept. So, use of mixing chamber in engines with m<6 is provides the best results related to efficiency and acoustics.

In addition, with such configuration of engine an acoustic treatment of nozzle walls and shielding of external channel by a mixer is possible, that allows to reduce a fan noise radiated into a rear semi-sphere, and shielding of internal channel with a mixer and reduction of average speed of flow through a nozzle, resulted from mixing, reduce noise of turbine and jet stream itself. These measures are implemented in PS-90A2 engine.

17.1.8. Task 7. Development of high-quality CAA (Computational aeroacoustics) methods of noise modelling, and integration of project optimization at the level of system and subsystem (near and far-fields) into the methods

17.1.8.1. All European projects

Among researches performed within the frames of the integrated Clean Sky program the activities aimed at the development of methods of forecasting and calculation of a noise generated by individual elements and an aircraft in general, take a significant place. Publication [78] represents the results of recent achievements in forecasting of aviation noise including the development of new numerical models and calculation devices supported by expansion of the database of noise measurements made on commercialized airfields. Models and tools described in publication [78] are aimed at optimization of operational procedures, improvement of understanding the reasons of noise, definition of noise maps at realistic airfields and, consequently, reduction of noise pollution caused by commercialized aviation transport. This publication includes examples of comparisons of forecasted and field measurements, and also measurements of noise made in Heathrow airport. Effects of trajectory deviation are shown for takeoff and landing. Airbus A320-211 and Boeing B747-400 aircraft are the objects of research.

Noise modelling for A/C in FLIGHT project is based on a network of sub-models connected via a driver of higher level. This strategy makes it possible to replace the sub-model by another object without significant changes in software. For example, two models of jet noise, and also three models of noise propagation are available: each of these models can be selected by the user. Figure 17.17 shows a network model.

Each component is represented as a numerical model, which can be replaced if an alternative is available. In addition, the component is represented as a local point in a general strategy of validation, which starts at the level of a component and transmits to a level of aircraft integration. Each network model depends on a number of parameters or assumptions (marked by dotted lines coming from a component); the results are in a direct dependence on these assumptions.

FLIGHT can be configured by using the known input data on noise measurement in order to forecast A/C echeloning noise. The examples are represented for arrival/landing.

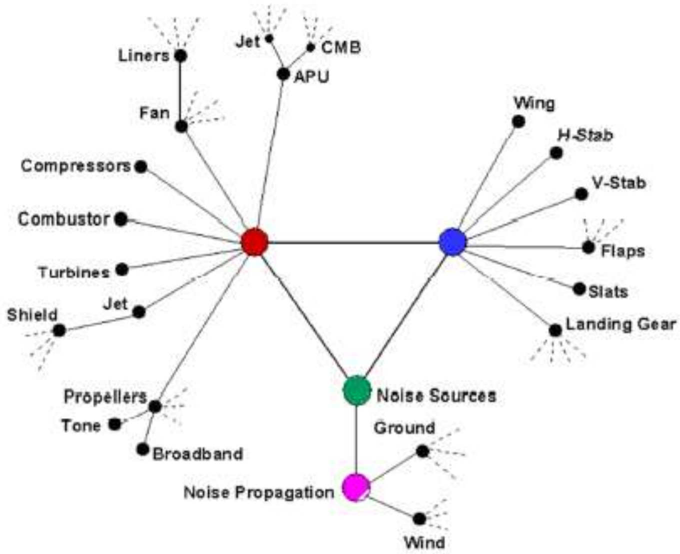

Figure 17.17 - NetwFork model of a tool modelling a noise of FLIGHT

Publication [79] shows a revision of characteristics and results of a flight test campaign on noise measurement performed for testing the noise models developed in Airbus Defence and Space GmbH within the frames of a medium-term outlook for noise reduction of military aircraft.

As based on a modular approach for various identified sources of noise (e.g., jet noise, fan noise, landing gear noise, etc.) the models were developed mainly on the basis of theoretical/study approaches, which require a clarification based on the noise data measured during special flight tests and subsequent checks (fig. 17.18).

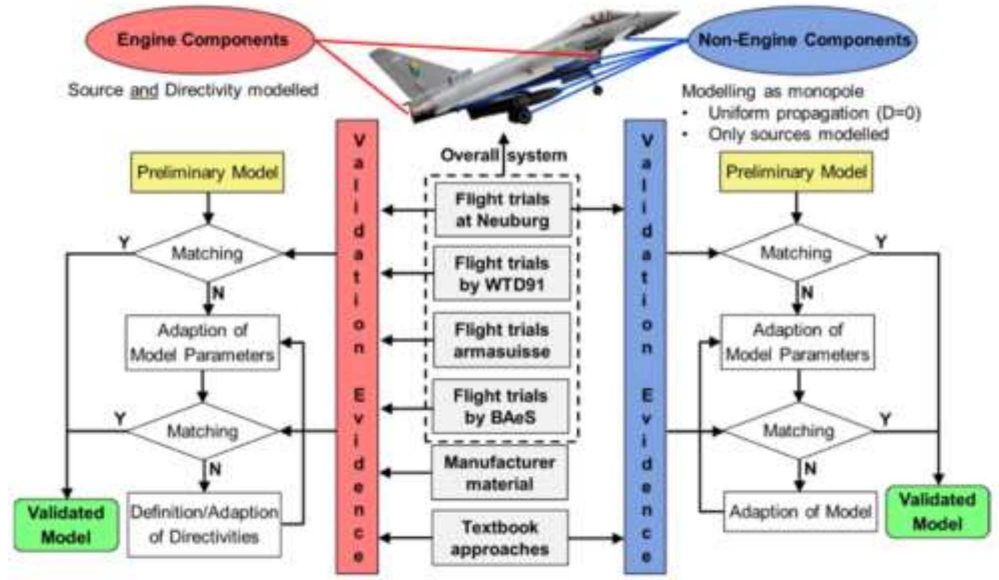

Figure 17.18 - Evaluation of noise model accuracy [57]

During a special flight test campaign conducted at airfields in Neuburg airport (Germany) noise was measured and the data were collected (fig. 17.19).

The obtained data made possible to study a contribution of individual noise sources and the directional characteristics for various noise sources (fig. 17.20).

Use of the obtained data allowed to clarify a developed general theoretical model of aircraft noise for forecasting acoustic emission.

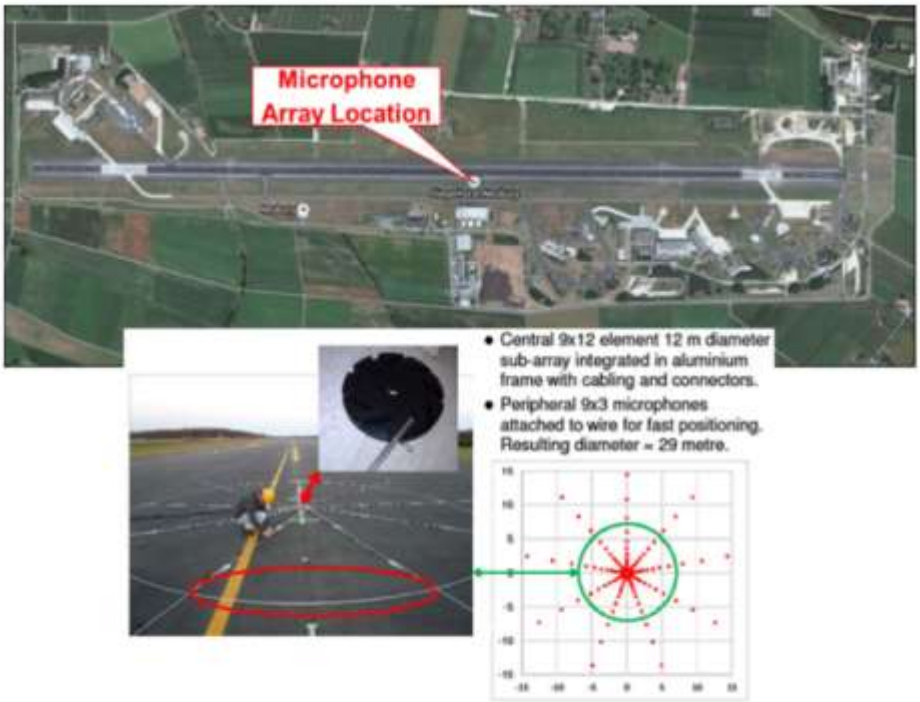

Figure 17.19 - Flight tests in Neuburg airport [79]

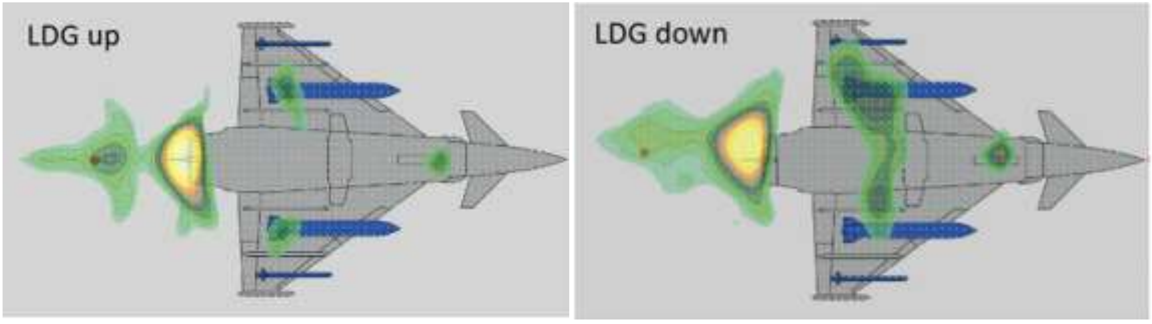

Figure 17.20 - Maps of intensity of landing gear sound (Reproduction band is 20 dB) [79]

A computer code capable to forecast aviation noise generated by a turboprop aircraft was developed in order to optimize the aircraft route for minimizing acoustic radiation within the scope of Turboprop and Propfan-Equipped Aircraft Noise Emission Model Flight-Noise-II (2011-2014) project [80].

Mechanisms of a broadband source of noise for UHBR fans were deeply studied, method of forecasting a broadband noise for UHBR fans was developed as the result of completing Improvement of Fan Broadband Noise Prediction: Experimental investigation and computational modelling – PROBAND (2005-2008) project [81].

The main objective of Experimental characterization of turbulent pressure fluctuations on realistic Contra-Rotating Open Rotor (CROR) 2D airfoil in representative high subsonic Mach number - CRORTET (2016-2018) project is the development of a database of high quality for future use in high-accuracy numerical calculations of a broadband noise.

The main tasks of validation of improved turbomachinery noise prediction models and the development of novel design methods for fan stages with reduced broadband noise – TurboNoiseBB (2016-2020) project is the development of the experimental base, the method of forecasting a broadband noise of fan, the development of fans with low level of acoustic radiation by using the developed method [82].

Simulations of CROR and fan broadband noise with reduced order modelling - SCONE (2017-2020) project is aimed at the development of "quiet" engines CROR and UHBR.

SCONE project involves three objectives: the development of improved statistical data on turbulence in order to use them in semi-analytical models with implementation of high-accuracy CFD methods, provision of the tested high-accuracy methods for calculations of a direct broadband noise, and improvement of analytical models [83].

17.1.8.2. National projects and research of Europe countries including associated

In publication [84] an innovative comprehensive approach to noise calculation by using NUMECA program module was proposed as approved for forecasting a noise generated from fan into a front semi-sphere with accounting a design of nacelle.

Great Britain. Possibilities of a program of modelling A/C noise are described in publication [85]. The program is set up on the basis of the implemented simulating models and is provided with modules for forecasting geometric configurations, aerodynamics, flight dynamics, general characteristics of aircraft and acoustics by using a number of noise models.

Currently, the scientific community is involved in the development of approaches for providing a large aircraft and the manufacturers with an aeroacoustic forecasting of a whole aircraft. It is a final objective of a multidisciplinary Hole Aircraft Multidisciplinary noise design system – HARMONY program conducted in partnership between Rolls-Royce, Airbus, Bombardier companies, and Southampton and Cambridge universities [86].

HARMONY program includes a working package for modelling a broadband noise of fan.

Broadband noise from turbofan engines, which is mainly stipulated by interaction of fan with a straightener, is a dominating source of noise at takeoff and landing (fig. 17.21).

This source of noise is also available in a bi-rotating fan (CROR) and wind turbines. Publication [86] represents the results of numerical studies performed with simplified models in order to have more fundamental information about traces beyond a fan, at a lower computational effort.

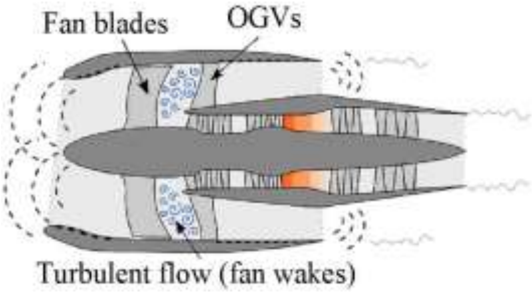

Figure 17.21 - Diagram of broadband noise of engine fan caused by interaction with straightener (OGV)

For a numerical calculation of noise a two-stage strategy is used.

Firstly, a synthetic method of turbulence based on a numerical filter and synthetical vortex methods is used for reproduction of statistics of fan turbulent traces.

Secondly, this artificially developed turbulence is entered into a computational code of aeroacoustics, which solves linearized Euler equations for modelling interaction between the fan blade rings.

To estimate accuracy of the represented strategy the results of a numerical calculation of noise are compared with an analytical model of flat plate cascades. Comparison of results showed that accuracy of the numerical calculation is higher than 3 dB.

Isotropic turbulence and spatio-temporal variations of turbulence intensity, scales of integral length by using cyclostationary spectral analysis are researched in the article. The results of the numerical modelling show that isotropic turbulence can be used for reproduction of fan traces averaged circumferentially without effects on a subsequent calculation of noise.

In addition, research of parameters is proposed in publication [86] for evaluation of effect of airfoil section geometry made on noise of airfoil section including thickness of airfoil section, central line and angle of attack.

The research results in a first approximation [86] show that noise reduction at high frequencies depends on thickness of airfoil section. This fact is in a coincidence with the research results related to the effect of a leading edge of isolated sections made on a noise level.

Besides the development of program codes for forecasting noise of individual sources of A/C and power plant, a development of experimental data base of acoustic emission for individual elements and system of aircraft in general, is important.

France. Hybrid method of noise forecasting is discussed in publication [87]. Aeroacoustic hybrid method is offered, a final goal of this method is a numerical forecasting of aviation noise. Aeroacoustic hybrid methods are applied more intensively to solve the problems of aviation noise as the alternative to direct numerical methods.

17.1.8.3. Projects and research in countries out of Europe

Russian Federation. 3DAS (3 Dimensional Acoustics Solver) [88] calculation method was developed in CIAM. Mathematical model for calculation of tonal noise of turbomachinery, which makes possible to describe effects of nonstationary aerodynamic interaction in the system of several mutually rotating blade rings was developed. Model is supported by the analysis of a frequency-modal pulsations of parameters of gas flow in the turbomachinery which allows to establish a spatio-temporal structure of a disturbance field induced by interaction of rotor and stator blade wheels. Method of calculation of tonal noise is implemented in CIAM program 3DAS complex with use of high-efficient difference schemes of a numerical integration of Euler equations for flow parameter pulsations.

Publication [89] offers a new high-effective method of numerical modelling of 3D tonal acoustic fields at frequencies of blade movement and their highest and combination harmonics generated by a fan of aero engine.

USA. Publication [90] discusses possibilities of a program module for forecasting a noise generated from modern aircraft at climbing, cruising flight and descending. Aircraft noise generated at climbing, cruising flight and descending (noise in route) can be as irritating as that generated at takeoff and landing, particularly in country regions with lower level of environment noise. Program of forecasting noise generated by A/C in route is proposed. The program allows to calculate a noise level for modern engine and aircraft configurations.

Publication [91] represents a fundamental analysis and discussion of F-35B aircraft acoustic emission within a wide range of engine operational power settings. Complex researches conducted by USAF laboratory with F-35A and F-35B aircraft for estimation of acoustic emission under all operational power settings of engine showed that a radiation direction is forwardly shifted with increasing of engine rotational speed and power.

Publication [92] describes a research of F-22 aircraft acoustic emission at a reheat thrust. Authors obtained the data related to noise sources as based on a spectrum analysis. When engine is operated under reheat power a new dominating acoustic source associated with fuel burning in afterburner, which on directional diagram features a maximum radiation at angles of 110° to 130° and at frequencies exceeding 200Hz is appeared in a total acoustic radiation.

First Section Conclusions

Acoustic perfection is one of the most important requirements of modern and advanced aero engines.

Revision of all-European projects, national projects of European countries, and also research conducted in countries out of Europe are represented as related to SRIA 7 subtasks on reduction of noise from aero engines (Challenge 3. Protecting the environment and energy supply - Reduce aircraft noise associate with the propulsive system).

The represented revision showed that in order to reduce noise of power plant the intensive researches are conducted in countries of Europe and out of Europe.

Acoustic emission can be reduced due to the development of projects aimed at:

- development of sound-absorbing structures;
- research of optimum designs of fan reduction gear;
- acoustic and aerodynamic improvement of fan blade shape;
- research of boundary layer control;
- development of composite materials use;
- further acoustic improvement of engines (Open Rotor);
- research of active control of acoustic stream by using micro-streams and a combination of active noise control with use of chevron nozzles;
- reduction of noise of internal sources; compressor and air bleed valves, combustion chamber;
- improvement of modelling methods.

17.2. Methods of assessment of the noise-reduction research initiatives

17.2.1. Methods of assessment of the technology and manufacturing readiness

The readiness assessment concept is the system (model) of readiness levels (RL) that is organized as a special scale of developments status characteristics evolving in time. In the framework of the concept, the principles (criteria) of evaluation of the status are formulated such as project gates and methods of the assignment of a certain development to a certain readiness level (RL).

To illustrate this conceptual approach, the most known scale of technology readiness assessment (Table 17.3) can be given.

Technology risk level	Technology readiness level	Technology status
0	9	Standard use
20	8	Technology is tested and certified
30	7	Technology demonstration in operational conditions
40	6	Technology demonstration on model or prototype
50	5	Mockup is checked in near- to- real life operating conditions
60	4	Mockup is tested in laboratory conditions
70	3	Experimental or computationl verification of concept
80	2	New technology concept is defined
100%	1	Basic principles of new technology are identified.

Table 17.3 - Technology readiness level system with scale of technology risk levels

The existing classification reflects the status of research programs in relation to the current technology readiness level (TRL). The TRL model objectifies the readiness assessment, makes it easier for customers and developers to monitor the process of development and selection of technologies, which are maximum ready for the system integration and industrial introduction. The TRL assessment scale allows ranking of technologies by maturity (readiness), from the most immature level, TRL 1, to the most mature level, TRL 9. The scale ensures comparability of seemingly incomparable technologies due to their standardized description [93].

Each TRL is assigned with a certain technical risk (or certain range of risk values).

The risk reduces in direct proportion with the increase in the technology readiness (Table 17.3).

Such formalization allows the parties (subjects) of the process of complex engineering systems development to make a standardized objective assessment and arrange financing for specific activities on the operational development of specific technologies, that is, on a targeted improvement of the readiness level of the technologies rather than an abstract development of the industry on the whole.

To date, the technology readiness level assessment methodology has grown vigorously as a complex of objective and reliable techniques (tools), which are necessary for a rigorous assessment of technology maturity and provide insight into the risks leading to cost overrun, schedule delay, and decline in production.

A range of qualitative and quantitative techniques has been provided that are used for the assessment of technological and manufacturing readiness (Table 17.4). What is more, techniques (scales) are developed that make it possible to assess the technology maturity and readiness of States.

Tools	Description
Qualitative Maturity Assessment Techniques	
Manufacturing Readiness Level (MRL)	The MRL is a 10-level scale used to define current level of manufacturing maturity, identify maturity shortfalls and associated risks, and provide the basis of manufacturing maturation and risk management
Integration Readiness Level (IRL)	The IRL is a 9-level scale intended to systematically measure the maturity, compatibility, and readiness of interfaces between various technologies and consistently compare interface maturity between multiple integration points. Further, it provides a means to reduce the uncertainty involved in maturing and integrating a technology into a system
TRL for Non-System Technologies	Expansion of the TRL definitions to account for non-system technologies such as processes,methods, algorithms, and architectures
TRL for Software	Expansion of the TRL metric to incorporate other attributes specific to software development
Technology Readiness Transfer Level (TRRL)	The TRRL is a 9-level scale describing the progress of technology transfer to a new application. It expands and modifies the TRL definitions to address the transfer to space technology into non-space system
Missile Defense Agency Checklist	A tailored version of the TRL metric specifically in support of hardware maturity through the development life cycle of the product (Mahafza 2005).
Moorhouses Risk Versus TRL Metric	A 9-level metric mapping risk progression analogous to technology maturity progression. The TRL descriptions are tailored specifically toward UAV
Advancement Degree of	Leveraging the concept of R&D^3, the AD^2 augments TRLs by assessing the difficulty of advancing a technology from its current level to a desired

Difficulty (AD^2)	level on a 9-tier scale
Research and Development Degree of Difficulty (R&D^3)	The R&D^3 is a 5-level scale intended to supplement the TRL by conveying the degree of difficulty involved in proceeding from the current TRL state to desired level, with 5 being very difficult and 1 being least difficult to mature the technology
Quantitative Maturity Assessment Techniques	
System Readiness Level (SRL)	The SRL is a normalized matrix of pair-wise comparisons of TRLs and IRLs of a system. It is a quantitative method providing insight into system maturity as a product of IRL x TRL
SRLmax	The SRLmax is a quantitative mathematical model aiming to maximize the SRL under constraint resources. The objective of the SRLmax is the achievement of the highest possible SRL based on the availability of resources such as cost and schedule
Technology Readiness and Risk Assessment (TRRA)	TRRA is a quantitative risk model that incorporates TRLs, the degree of difficulty (R&D^3) of moving a technology from one TRL to another, and Technology Need Value (TNV). The TRRA expands the concept of the risk matrix by integrating "probability of failure" on the y-axis and "consequence of failure" on the x-axis
Integrated Technology Analysis Methodology (ITAM)	ITAM is a quantitative mathematical model that integrates various system metrics to calculate the cumulative maturity of a system based on the readiness of its constituent technologies. The system metrics include TRLs, ΔTRL, R&D Degree of Difficulty (R&D^3), and TNV (Mankins 2002).
TRL for Non- Developmental Item (NDI) Software	A mathematical method to assess the maturity of Non- Developmental Item (NDI) software using orthogonal metrics in combination with a pair-wise comparison matrix to examine two equivalent technologies that are candidates for insertion into a system. Incorporates other attributes such as requirement satisfaction, environment fidelity, criticality, product availability, and product maturity
Technology Insertion (TI) Metric	TI involves the integration of various metrics that deal with insertion of technology and subsystems into a current system in order to develop an "enhanced system." The TI Metric is a high-level metric computed from sub-metrics or dimensions intended to evaluate the risk and feasibility of technology insertion from a subsystem and a system level
TRL Schedule Risk Curve	This is a quantitative model that does not communicate the maturity of technology at a certain point in time but instead leverages the TRL metric to identify the appropriate schedule margins associated with each TRL level in order to mitigate schedule slips

Table 17.4 - Qualitative and quantitative techniques used to assess technology and manufacturing readiness [93]

In addition to the readiness indices listed in Table 17.2.1.2, other readiness level indices (including those related to project readiness) are used. Specialists distinguish [93]:

- Capability Readiness Levels – capability readiness levels of the assessment;
- Human Readiness Levels – readiness levels of human resources (staff);
- System Readiness Levels (SRL);
- Logistics Readiness Levels;
- Operational Readiness Levels;
- Design Readiness Levels – readiness levels of exterior (design);
- Software Readiness Levels;
- Innovation Readiness Levels;
- Programmatic Readiness Levels.

The 9-level scale of TRL has already become traditional in relation to the description of technology readiness.

17.2.2. General characteristics of Technology Readiness Level method

The Technology Readiness Level (TRL) scale was developed in the 1970s and 1980s in the United States, by the National Aeronautics and Space Administration (NASA) to grade the development of new technologies. Currently, TRL is widely used in US departments, organizations and companies such as the Department of Defense, the Defense Advanced Research Projects Agency (DARPA), the Air Force, the Federal Aviation Administration, the Department of Energy, NASA, the Air Force Research Laboratory, Ford, Boeing, Northrop Grumman, Lockheed Martin, GE, Kodak, etc. [94].

Europe is no exception, where this scale of technology readiness levels is used by companies, agencies and organizations such as the European Space Agency, the British Ministry of Defense, Nokia, Airbus, Rolls-Royce, BMW, FIAT, French energy companies, etc. At the same time the TRL system has been tested in Japan and Canada, for example, TOYOTA, Bombardier and others.

It is noteworthy that the scale initially included only seven technology readiness levels, and then was expanded to nine levels currently used. The specified measuring scale permits to estimate a condition of research works depending on the current level of TRL that promotes simplification of the control over a course of research works by developers and customers and the most optimum choice of the technologies most ready for industrial introduction. This scale is a very useful tool with which all projects are carefully monitored. The project cannot be promoted until the previous level has been successfully passed. At the same time, this scale significantly simplifies the decision to start developing specific models of advanced technology.

The depth of elaboration of the projects being developed in NASA provides a multilevel assessment of technologies [94] (Fig.17.22):

- TRL 1 – approval and publication of fundamental principles of technology;
- TRL 2 – formulation of technological concept and assessment of the possible field of application;
- TRL 3 – the beginning of active research and development, theoretical and experimental proof of operability of the presented concept;
- TRL 4 – testing in laboratory environment of the main technological models and components;
- TRL 5 – approbation of the main technological components in real conditions;
- TRL 6 – testing of a model or prototype in real conditions;
- TRL 7 – demonstration of test item or prototype in service;
- TRL 8 – completion of development and testing of the system in operation;

- TRL 9 – demonstration of technology in its final form during prototype testing.

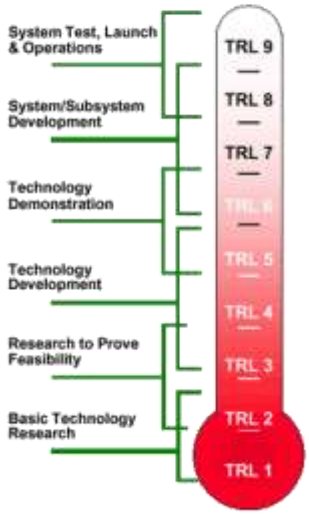

Figure 17.22 – Technology Readiness Level (TRL) scale

Each of the indicated readiness levels in this scale characterizes the depth of elaboration of the developed technology in order to create the final product. The levels of TRL: 1 thru 4 corresponds to the stage of formation at which the technology and test are evaluated; TRL: 5 thru 7 is the stage of development or pre-production; and TRL: 8 thru 9 is the stage of maturity or direct implementation of production.

The TRL scale makes it possible at each stage to assess the level of technology readiness with the help of questions containing both quantitative and qualitative indicators. When making decisions about technology readiness, the assessment of relevant research specialists specializing in this field of knowledge, research organizations and companies is used.

However, a more objective assessment of technology readiness can be provided by independent experts who have a broader outlook than the direct developers, and are not overly optimistic about the likelihood of success of the invention. In particular, the expert commission of the appropriate level and direction, which includes scientists, engineers and industry representatives, decides on the achievement of technologies of a certain readiness level. At the same time, scientists play a dominant role at lower levels of TRL, and industry representatives – at high levels.

17.2.3 System of assessment of technology readiness levels in relation to research works

Technology readiness level 1 (TRL 1) – is the most primitive level of technology readiness, at which the study of physical phenomena and effects that have theoretical and experimental justification takes place, and formulates ideas about the possibility of using these effects and phenomena in new technologies.

Experimental studies can be performed to confirm the obtained results. Experimental validation may include demonstration on the simplest laboratory equipment in model conditions of a physical effect or phenomenon, on the basis of which the technology can be further created. Theoretical substantiation can contain only the solution of model problems demonstrating the presence of effects that permit to create a new technology. It is assumed that in the further development of the theme, the effects may not be confirmed in more complex conditions or in more complex geometry of structures.

The result at this level will be the reception of fundamental principles of breakthrough technologies. To decide on the transition to TRL 2, the project is evaluated by experts on the following indicators [95]:

- a simplified calculation of environmental parameters is performed;
- the physical laws and assumptions used in the new technology are defined;
- "paper" research confirms the fundamental principles;
- initial scientific observations are described in journals, conference proceedings, technical reports;
- the basic scientific principles are formulated;
- project sponsor, source of funding, safety rules, including handling of hazardous materials are identified;
- the research hypothesis is formulated;
- the key characteristics of the studied object are revealed;
- executors and place of carrying out scientific researchers are defined.

Technology readiness level 2 (TRL 2) is a theoretical stage in the development of new technologies. The result of this stage will be a well-formulated concept with a theoretical basis. It is assumed that in the further work on the implementation of this concept, the final result may not be obtained. At this level, it is necessary to substantiate the possibility of creating new technologies that use physical effects and phenomena confirmed at the level of TRL 1. To achieve this level of technology readiness, it is necessary to have a well-formulated concept for the application of the detected physical effects, which allows the creation of new technology to solve an existing problem or create a product with new functional properties. At the specified stage there is a selection of works for the subsequent development of technologies. The selection criterion is the validity of the concept, which is assessed by an expert group. To decide on the transition to the next level, experts evaluate the project on the following indicators [95]:

- the customer is identified and interested in the technology;
- the potential of the system and its components is revealed;
- "paper" studies show that the application of technology is feasible;
- the obvious theoretical or empirical design decision is revealed;
- key elements of the technology are identified;
- the components of the technology are partially characterized;
- the productivity of each element of technologies is forecasted;
- modelling was performed to check the physical characteristics;
- the structure of the system is determined in accordance with the most basic principles;
- accurate analytical research confirms the fundamental principles;
- analytical research is published in journals, conference proceedings, technical reports;
- function of individual elements of technology;
- it is known which devices will be received at the output;
- preliminary strategy has been developed to achieve Readiness Level 6 (content, objectives, deadlines, costs, etc.);
- opportunities and limitations of researchers and research institutions are revealed;
- the volume and extent of waste at development process are defined;
- the need for experiments is identified;
- the qualitative characteristic of degree of risks (expenses, terms, results) is carried out.

Technology readiness level 3 (TRL 3) is an analytical and (or) experimental proof of effectiveness of the formulated concept of creating a new technology that confirms TRL 2. At this level it is necessary to substantiate this concept by demonstrating it on small-scale models for which technology is developed or computational models, taking into account the main points of the developed technology. In this case, this concept should contain the most fundamental details that are required to demonstrate the performance of new technology. The technology questions that experts need to answer in order to move to the next level are presented below by the following list of indicators [95]:

- integration of processes and safety requirements into the design process;
- identified key parameters of the technology and associated risks;
- analytical studies have confirmed the performance forecasts of each element of technology;
- basic research has been confirmed in the laboratory;
- the possibility to build mathematical / computer models;
- an assessment of the preliminary operational characteristics and measures of the system;
- the performance forecasts of each element of technology were evaluated by modelling;
- the representative of the customer who will interact with group of developers is identified;
- the customer takes part in requirements generation;
- design methods are developed and defined;
- "paper" studies show that system components can work together;
- the performance metric for the system is set;
- scaling research is initiated;
- the current manufacturability of the concept is estimated;
- sources of key components for laboratory/bench tests are identified;
- the scientific expediency of the project is demonstrated;
- analysis of the current state of recent developments shows that technology meets the needs;
- risk areas are identified;
- the strategy of risk minimization is revealed;
- the elementary functional and cost analysis of the performed operations is carried out;
- waste from the technology and place of waste storage are identified;
- individual components of the system are tested in the laboratory environment.

Technology readiness level 4 (TRL 4) – is a demonstration of technology performance in laboratory conditions on sufficiently detailed research models. An essential condition for passing this level of development of new technologies is the scale of the studied models; it must correspond to the intermediate scale and contain a sufficient number of details of hardware design. The assessment of technology readiness level in order to move to the next stage is carried out by analyzing the following indicators [95]:

- key process variables are fully identified and a preliminary assessment of technology hazards is conducted;
- individual components of the technology are tested in the laboratory or by the customer;
- subsystems consisting of several components are tested in the laboratory using their simulators;
- general system requirements for end users are documented;
- system of performance indicators was established;
- laboratory experiments with available components show their joint performance;
- the output or completion criteria of technology agreed with by the project sponsors are demonstrated;
- technologies demonstrate basic functionality in the simulated environment;
- prototypes of technology are made;
- the project of a conceptual design is documented (the description of system, technological schemes, general layout drawings, material balance);

- research integration is initiated;
- formal risk management program is initiated;
- the key manufacturing processes for the equipment are defined;
- scaling of documents and technology designs is completed;
- functional description of the process is developed;
- testing of low technological integration at the system level in the laboratory, which is characterized as low, is completed;
- process/parameter constraints and control safety strategy are analyzed, etc.

Technology readiness level 5 (TRL 5) – is a demonstration of technology performance level on sufficiently detailed models of the devices being developed in bench conditions or in full-scale conditions. At this level, not prototypes are tested, but only detailed models of the devices being developed. To proceed to the next stage, the following indicators should be analyzed [95]:

- the relationship between the main systems and subsystem parameters is revealed in laboratory conditions;
- parameters of components available for testing are set;
- system requirements for the user interface are identified;
- preliminary design is started;
- managed to establish requirements for technology verification;
- interactions between components in testing are realistic;
- equipment prototypes of system components are created;
- target indicators of availability and reliability are determined;
- technology safety functions are tested;
- 3D drawings and technological schemes are completed;
- definition of requirements containing performance thresholds and final factory design of technology;
- Pre-Feasibility Study Report is completed;
- the integration of system modules/functions is demonstrated in laboratory environment;
- formal control of all components of the prototype is carried out during final testing;
- the whole range of physical and chemical properties of the system is determined;
- waste simulators are developed;
- testing has confirmed that the properties / performance of the simulators is consistent with the properties and performance of actual waste;
- laboratory tests are carried out using a prototype system and simulators;
- laboratory tests were carried out using a limited amount of real waste and a prototype system;
- the system design is checked;
- the results of studies of simulators and real waste are consistent;
- the limitations for all process parameters and control safety are elaborated;
- testing of the engineering documentation verification plan is completed;
- the risk management plan is documented;
- the process of risk analysis, revision of the inventory of hazardous materials and determination of the level of safety management for the corresponding draft design, etc. are carried out.

Technology readiness level 6 (TRL 6) – at this stage, it is necessary to demonstrate the technology performance on prototypes of equipment under development in bench conditions or in conditions close to real ones. The scale of the systems under development should already be full. This level is the highest level of technology development at which research and development work is carried out. If this technology successfully demonstrates its efficiency, then in this case a decision is made on its further implementation in specific industrial products. This requires the fulfillment of the following indicators [95]:

- the technical indicators revealed the relationship between the system and subsystem parameters;
- the availability and reliability of the system levels are established;
- the integration of security into the design process is made;
- the operating environment for the final system is identified;
- the collection of the actual maintainability, reliability and maintenance of the system data is initiated;
- the baseline performance determination (including total project cost, schedule and scope) is completed;
- operational limits for components are identified (ranging from design, safety, environmental compliance, etc.);
- operational requirements documents are available;
- for the engineering design of large-scale systems, operating errors are determined;
- technical interface system is defined;
- the integration of the prototype is demonstrated according to technical parameters;
- project analysis ensures that technology is available on demand;
- process control interface is created;
- a program to count the stages of creating the final design is purchased;
- a prototype of critical production processes is created;
- most of the pre-production equipment is available for system manufacturing;
- the technical feasibility of the system is fully demonstrated;
- the design specification technology is fully completed and ready for detailed design;
- a high quality functional prototype of the operating system is obtained;
- final technical data report is completed;
- engineering and industrial tests were carried out on a full set of simulators using system prototypes;
- the results of laboratory, engineering experiments and prototype tests do not contradict each other;
- a demonstration of production has been fully carried out (at least once);
- the processes of risk analysis, inventory of hazardous materials and determination of the level of safety management at the preliminary / final phase of the project, etc. are completed.

Technology readiness level 7 (TRL 7) – is demonstration of a prototype system in operating conditions. At this level of technology development, work is being carried out to introduce the technology into a real device, which must demonstrate its efficiency.

Technology readiness level 8 (TRL 8) – at this level a real device assembly takes place under conditions close to real ones. This requires demonstrating the functionality of the new technology for a specific device in combination with the operation of other devices.

Technology readiness level 9 (TRL 9) demonstrates the performance of real system in real conditions, after which a decision is made to apply the technology on serial products.

The advantages of this method for ranking the possible states of the technology creation process:

- objectivity in assessing the state of technology development;
- providing a general understanding of the status (state) of specific technology and the entire scientific and technical task;

- obvious risk management;
- use for decision-making regarding technology financing;
- use for making and monitoring the implementation of decisions concerning the technology transfer to the next maturity (readiness) level;
- technology transfer.

The disadvantages include:

- an increase in reporting, the volume of documentation and the need to form a special database or a separate information system;
- for the assessment itself, subjective tables of input parameters ("calculators") are used;
- a relatively new method takes time to master in order to track the subsequent impact on the system;
- the necessity to make changes to the current regulatory legal and instructive regulatory framework.

The TRL method does not cover the following questions:

- production cost;
- availability of all the necessary materials in required quantity;
- the possibility of transferring production from an experimental laboratory to a mass full-scale production.

Using TRL, it is possible to describe the technology in terms of its flexibility and relevance, and the presence of a single methodology allows specialists of different levels to use unified approaches.

The TRL method makes it possible to obtain information about the status of technology and possible risks for all participants in the process. Using TRL provides consistent support for the full innovation cycle of technology, consisting of stages of knowledge generation, transformation of knowledge into experimental development and technology commercialization.

TRL allows:

- to determine the degree of technical readiness for the analyzed technology, being an auxiliary element to support the decision-making system for its development and implementation;
- to track and control technological progress in the course of technology development;
- to establish the degree of complexity of the technology and assess possible risks.

Despite the widespread use of the TRL method, for assessing the level of technology feasibility, such parameters as organizational readiness, risks and competitive advantages, market readiness and team competence are also important (Figure 17.23). This is a range of questions that confirm market readiness and commercialization level (Commercialization Readiness Level).

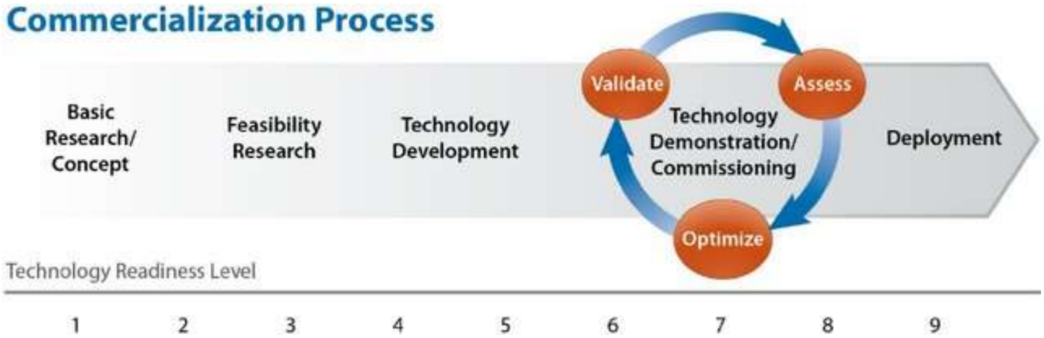

Figure 17.23 – Comparison of TRL and commercialization process [95]

In the current conditions, the transfer of technologies, that is, their promotion into the real economy, is no less important for commercial success than the movement of capital.

The transfer of technologies, that is, their transfer from one carrier to another, has become an integral part of the global economic process, and the work of organizations in the scientific sector around the world is more and more evaluated in terms of cost-effective use of technologies in the world market.

Comparison of technology development level and market requirements permits to understand at what stage of development it is, and what is the distance to the market. This assessment permits to start shaping a technology promotion strategy.

Thus, for a comprehensive assessment, it is necessary to use both the Technology Readiness Level method and the Commercialization Readiness Level method.

17.2.4 Method of TRL/CRL determination

In order to determine the Technology Readiness Level and Commercialization Readiness Level, you can use the classic calculating tool NYSERDA (Technology & Commercialization Readiness Level Calculator).

The calculator provides 7 criteria:

1) Technology
2) Product development
3) Product definition / design
4) Competitive landscape
5) Team
6) Go-to-market
7) Manufacturing/ Supply chain

Each criterion has 5 sublevels.

The procedure for calculating the Technology & Commercialization Readiness Level using the classic calculating tool NYSERDA was carried out as follows. On the basis of information available in the open press (abstracts of scientific conferences, scientific articles, monographs, websites on aviation topics of a scientific nature), information about the technology under study was analyzed. After that, the authors gave answers to questions according to 7 criteria (presented above) regarding this technology. To determine the Technology & Commercialization Readiness Level of a particular technology under study, the mathematical apparatus set in the NYSERDA calculator was used.

Using the NYSERDA calculator makes it possible to determine the technology readiness level under consideration when evaluating in a complex.

It should be noted that any assessment is approximate, since the mass coefficients corresponding to all parameters are obtained as a result of statistical generalizations that have conditional (conventional) reliability.

Second Section Conclusions

The section provides a description of methods for assessing the technological and production readiness of technologies. To further assess the technological and production readiness of noise reduction technologies, the Technology Readiness Level methods and the Commercialization Readiness Level method were selected.

Using TRL, it is possible to describe the technology in terms of its flexibility and relevance, and the presence of a single methodology allows specialists of different levels to use unified approaches. The advantages of this method for ranking the possible states of the technology creation process are the following:

- objectivity in assessing the state of technology development;
- providing a general understanding of the status (state) of specific technology and the entire scientific and technical task;
- obvious risk management;
- use for decision-making regarding technology financing;
- use for making and monitoring the implementation of decisions concerning the technology transfer to the next maturity (readiness) level;
- technology transfer.

The disadvantages include:

- an increase in reporting, the volume of documentation and the need to form a special database or a separate information system;
- for the assessment itself, subjective tables of input parameters ("calculators") are used;
- a relatively new method takes time to master in order to track the subsequent impact on the system;
- the necessity to make changes to the current regulatory legal and instructive regulatory framework.

The TRL method does not cover the following questions:

- production cost;
- availability of all the necessary materials in required quantity;
- the possibility of transferring production from an experimental laboratory to a mass full-scale production.

Organizational readiness, risks and competitive advantages, market readiness and team competence must additionally be assessed using the Commercialization Readiness Level method.

In order to determine the Technology Readiness Level and Commercialization Readiness Level, you can use the classic calculating tool NYSERDA (Technology & Commercialization Readiness Level Calculator).

17.3. Results on evaluation of research initiatives on the problem of reducing the aviation transport noise rate

17.3.1 Evaluation of the Technologies Readiness Level

This section presents a preliminary evaluation of the technologies readiness level obtained by the authors as well as the market readiness and commercialization level for 14 innovations based on the methods presented in subsection 2.4.

To make an evaluation, the method of Technology Readiness Level (TRL) and the method of Commercialization Readiness Level (CRL) are used in this work. Comparison of TRL / CRL development will provide an opportunity to compare the development of various technologies. In this section, technologies that are developed in the countries of the European Union and technologies that are developed in the Russian Federation and the USA are selected.

Calculating tool NYSERDA (Technology & Commercialization Readiness Level Calculator) is used as software.

The results of evaluation of technologies readiness and market readiness and commercialization level for 14 innovative technologies developments:

17.3.1.1 Countries of the European Union

Technology No. 1 - Composite fan blade (Rolls-Royce)

Rolls-Royce Company designs engines under programs Advance and Ultra Fan that are to be completed in 2020 and 2025 respectively. The inculcated technologies make possible to reduce engine weight and raise fuel efficiency by 20% for Advance and by 25% for Ultra Fan, decrease the noise and hazardous emission level [98]. The fan noise is reduced due to employment of the reduction gear, improved shape of fan blades with due regard to multi-parametric optimization of aerodynamic and acoustic behaviour as well as making of blades from composite materials.

The results of TRL&CRL evaluation of fan blade for future Rolls-Royce engines: TRL=8, CRL=4 (Fig. 17.24).

Technology No. 2 - OPEN ROTOR fan

In 2008, the European Union launched the DREAM project (ValiDation of Radical Engine Architecture systeMs). The aim of DREAM project was to output completely new design of the air engine combining efficiency of turboprop and power of turbojet, but free from their drawbacks. The European Union has attracted to the project 44 firms from 13 countries including Russia. In December 2017, Safran French air group performed ground test of the first engine with open rotor. The company expects that new structure will provide fuel saving by 15 % compared to LEAP-1 turbofan model, built by CFM International (Safran and GE Aviation) joint venture.

The result of TRL&CRL evaluation of Open Rotor propfan: TRL=6, CRL=4 (Fig. 17.25).

Technology No. 3 - Fan blade designed by Safran Company

Safran develops LEAP engine, which will have high ecological rates and high economy. Within those researches Safran Company designs fan blades, which will be able to ensure high acoustic efficiency.

The result of TRL&CRL evaluation of SAFRAN fan blade: TRL=7, CRL=4 (Fig. 17.26).

Technology No. 4 - Device for noise reduction in the airframe of the aircraft with turboprop engines

Within the research scope SFIDA, UNINA and NOVOTECH companies joined forces with LEONARDO - FINMECCANICA - AIRCRAFT DIVISION in order to design an advanced device for noise control, which will be installed on a turboprop aircraft of new generation [34].

The result of TRL&CRL evaluation of device for noise reduction in the airframe of the aircraft with turboprop engines: TRL=6, CRL=2 (Fig. 17.27).

Technology No. 5 - Sound absorbing structure (SAS) with 3D spiral cell of Safran Nacelles

Safran Nacelles carried out researches focused on the study of complex SAS [9].

Numerical studies of acoustic characteristics were conducted along with the model physical experiment, which confirmed the studies efficiency for SAS application in nacelles of the next generation engines in order to attenuate lower frequencies.

The specific shape of cells enables to reduce SAS thickness that will ensure reduction of nacelle weight.

The result of TRL&CRL evaluation of SAS with 3D spiral cell: TRL=3, CRL=2 (Fig. 17.28).

Technology No. 6 - Compressor fan blade with blowing out extra air mass into aerodynamic wake

The results of researches focused on reduction of tonal noise by the method of sectional blowing of air through the trail edge are shown in the work [21].

The result of TRL&CRL evaluation of compressor fan blade with blowing out extra air mass into aerodynamic wake: TRL=3, CRL=1 (Fig. 17.29).

17.3.1.2 Projects and researches outside Europe

The USA:

Technology No. 7 - Fan of Pure Power Turbofan series engines (first generation)

PurePower PW1000G is a family of turbofan bypass engines with high bypass ratio with reduction drive of the fan. Engine Pure Power PW1000G provides reduction of the noise level by 50...75 %, maintaining it by 15-20 dB lower than the standard, which is the strictest of all existing ones (ICAO Stage 4). Noise reduction of the fan is provided by decrease in rotational speed and by employment of a fan blade with a specific shape.

The results of evaluation of the fan according to TRL&CRL method: TRL=9, CRL=9 (Fig. 17.30).

Technology No. 8 – Fan of the Pure Power Turbofan series engines (second generation)

In 2017, Pratt & Whitney, aircraft engines manufacturer that is a part of United Technologies Corp. conglomerate, announced a completion of 175-hour program of second stage of ground tests of power plant with reduction drive of Geared Turbofan Fan (GTF) of the second generation.

Pratt & Whitney developments are focused on decrease in fuel consumption by 33 %, emissions of carbon dioxide by 60 % and noise level by 32 dB till 2030 in reference to the level in the year 2000. The engine fan has fewer blades [99].

The results of evaluation of the second generation fan for Pure Power Turbofan series engines according to method TRL&CRL: TRL=7, CRL=4 (Fig. 17.31).

Technology No. 9 – Fan of GEnx series engines

GEnx (General Electric Next Generation) is the family of turbofan engines, designed and manufactured by American company GE Aviation for Boeing 787 Dreamliner and Boeing 747-8 for replacement of CF6 engine in the range of the company.

The noise reduction is provided by the upgraded shape of fan blades in terms of aero-acoustic characteristics [96].

The result of TRL&CRL evaluation of fan for GEnx engines: TRL=9, CRL=9 (Fig. 17.32).

The Russian Federation:

Technology No. 10 - PD-14 fan

PD-14 engine of the fifth generation is developed in wide cooperation with companies of United Engine Corporation. The lead developer is JSC "UEC-Aviadvigatel", the lead commercial manufacturer is JSC "UEC-Perm Engines" [97].

The engine fan has hollow wide-chord titanium blades designed with regard to aerodynamic and acoustic characteristics.

The result of TRL&CRL evaluation of PD-14 engine fan blade: TRL=9, CRL=8 (Fig. 17.33).

Technology No. 11 - Fan with raked blades of the outlet straightener

As part of the work of CIAM, the researchers are conducted and are aimed at study of acoustic characteristics of a fan with raked blades of the outlet straightener. The researchers are conducted by numerical calculation (3DAS program) and experimentally by model C-3A [60].

The result of TRL&CRL evaluation of a fan with raked blades of the outlet straightener: TRL=3, CRL=2 (Fig. 17.34).

Technology No. 12 - Combined noise suppressor

Combined noise suppressor (SAS) is a rather efficient method to reduce noise, but future engines require development of SAS of more complex structures, for example combined noise suppressor developed by CIAM [11].

The result of TRL&CRL evaluation of combined noise suppressor: TRL=3, CRL=2 (Fig. 17.35).

Technology No. 13 - Use of micro-jets in a supersonic under-expanded jet

Experimentally it was found out that in case of supersonic under-expanded jet the noise level decreases essentially in the low-frequency region of the spectrum and a slight increase takes place at high frequencies. Use of micro-jet technology makes it possible to reduce the total noise level of a jet by 2-3.5 dB uniformly in the whole range of angles [22].

The result TRL&CRL evaluation of use of micro-jets in a supersonic under-expanded jet: TRL=3, CRL=1 (Fig. 17.36).

Technology No. 14 – Integration of power plant and aircraft

The most important field of work of CIAM specialists is a parameter optimization of PP of A/C for various purposes and various flight speeds by the optimality criteria: flight characteristics, fuel efficiency, carrier cost, life cycle hour cost, environmental characteristics, etc. [100].

The result of TRL&CRL evaluation of power plant and aircraft integration: TRL=2, CRL=2 (Fig. 17.37).

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

Technology & Commercialization Readiness Level Calculator

Profile	
Company/Organization Name:	Rolls Royce
Proposal Title:	Composite fan blade (titanium carbide)
Product/Innovation Description:	The configuration of fan blade is designed by taking into account the increase of acoustic and aerodynamic performance, the material – is titanium carbide.

Technology Readiness Level 8

Commercialization Readiness Level 4

Category	Answer
Technology	Laboratory scale integrated product/system demonstrates performance in the intended application(s)
Product Development	Actual product/system has been proven to work in its near-final form under a representative set of expected conditions and environments
Product Definition/Design	Comprehensive customer value proposition model has been developed, including a detailed understanding of product/system design specifications, required certifications, and trade-
Competitive Landscape	Competitive analysis to illustrate unique features and advantages of the product/system compared to competitive products/systems has been completed
Team	Balanced team with all capabilities onboard (e.g. sales, marketing, customer service, operations, etc.) running the company with assistance from outside advisors/mentors
Go-To-Market	Partnerships have been formed with key stakeholders across the value chain (e.g. suppliers, partners, service providers, and customers)
Manufacturing/Supply Chain	Manufacturing process qualifications (e.g. QC/QA) have been defined and are in progress

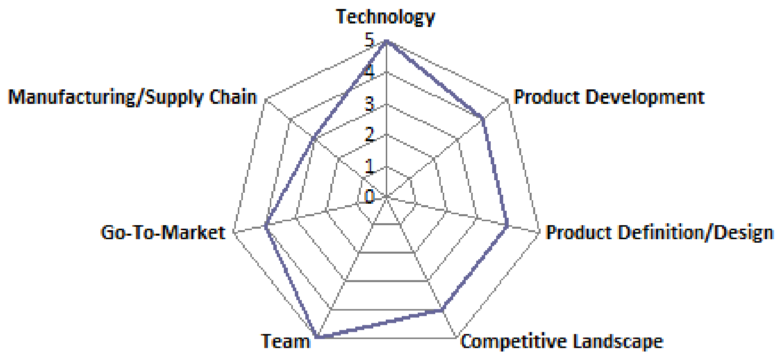

Figure 17.24 – TRL&CRL blades for the future Rolls-Royce engines

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

Technology & Commercialization Readiness Level Calculator

Profile	
Company/Organization Name:	Rolls Royce, SAFRAN, CIAM, TsAGI, etc
Proposal Title:	OPEN ROTOR
Product/Innovation Description:	Blade configuration and the number of open rotor blades are designed by taking into account the decrease in acoustic emission and increase in aerodynamic performance. Blades are made of composite material.

Technology Readiness Level 6

Commercialization Readiness Level 4

Category	Answer
Technology	Initial testing of integrated product/system has been completed in a laboratory environment
Product Development	Pilot scale product/system has been tested in the intended application(s)
Product Definition/Design	The product/system has been scaled from laboratory to pilot scale and issues that may affect achieving full scale have been identified
Competitive Landscape	Competitive analysis to illustrate unique features and advantages of the product/system compared to competitive products/systems has been completed
Team	Balanced team with all capabilities onboard (e.g. sales, marketing, customer service, operations, etc.) running the company with assistance from outside advisors/mentors
Go-To-Market	Market and customer/partner needs and how those translate to product requirements have been defined, and initial relationships have been developed with key stakeholders across the value chain
Manufacturing/Supply Chain	Manufacturing process qualifications (e.g. QC/QA) have been defined and are in progress

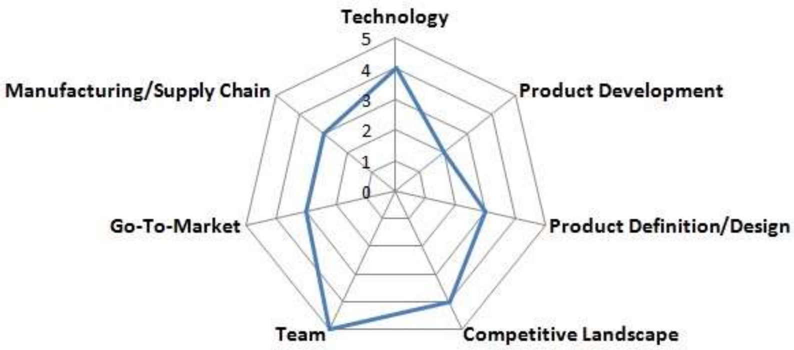

Figure 17.25 – TRL&CRL of Open Rotor engine

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

Technology & Commercialization Readiness Level Calculator

Profile

Company/Organization Name: SAFRAN

Proposal Title: Fan blade

Product/Innovation Description: Three-dimensional natural composite blade, designed by taking into account the decrease in acoustic emission and increase in aerodynamic load

Technology Readiness Level 7

Commercialization Readiness Level 4

Category	Answer
Technology	Laboratory scale integrated product/system demonstrates performance in the intended application(s)
Product Development	Demonstration of a full scale product/system prototype has been completed in the intended application(s)
Product Definition/Design	Comprehensive customer value proposition model has been developed, including a detailed understanding of product/system design specifications, required certifications, and trade-offs
Competitive Landscape	Competitive analysis to illustrate unique features and advantages of the product/system compared to competitive products/systems has been completed
Team	Balanced team with all capabilities onboard (e.g. sales, marketing, customer service, operations, etc.) running the company with assistance from outside advisors/mentors
Go-To-Market	Partnerships have been formed with key stakeholders across the value chain (e.g. suppliers, partners, service providers, and customers)
Manufacturing/Supply Chain	Relationships have been established with potential suppliers, partners, service providers, and customers and they have provided input on product and manufacturability requirements

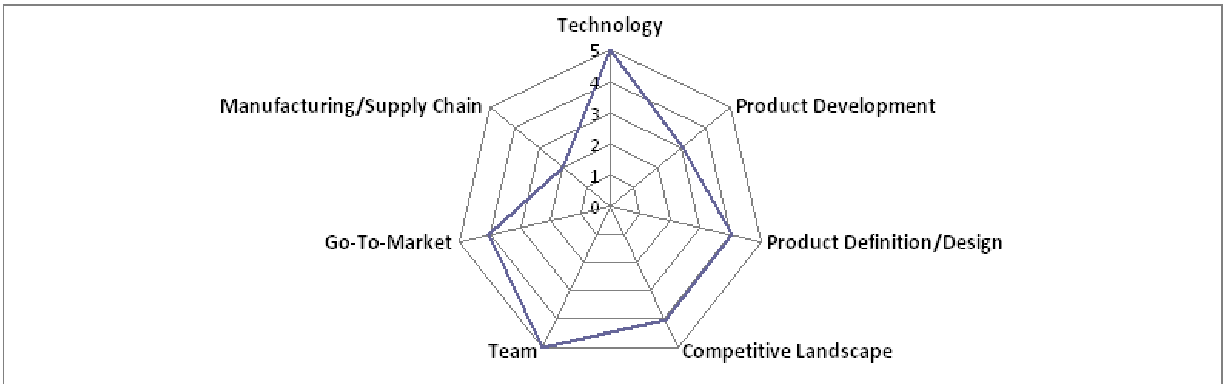

Figure 17.26 – TRL&CRL of SAFRAN fan blade

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

Technology & Commercialization Readiness Level Calculator

Profile	
Company/Organization Name:	SFIDA research project
Proposal Title:	Fuselage noise abatement device for turboprop aircraft
Product/Innovation Description:	Technology solution for improvement internal comfort (noise abatement) and dynamic characteristics of turboprop aircraft

Technology Readiness Level 6

Commercialization Readiness Level 2

Category	Answer
Technology	Initial testing of integrated product/system has been completed in a laboratory environment
Product Development	Pilot scale product/system has been tested in the intended application(s)
Product Definition/Design	The product/system has been scaled from laboratory to pilot scale and issues that may affect achieving full scale have been identified
Competitive Landscape	Primary market research to prove the product/system commercial feasibility has been completed and basic understanding of competitive products/systems has been demonstrated
Team	Balanced team with technical and business development/commercialization experience running the company with assistance from outside advisors/mentors
Go-To-Market	Customers/partners have been interviewed to understand their pain points/needs, and business model and value proposition have been refined based on customer/partner feedback
Manufacturing/Supply Chain	Relationships have been established with potential suppliers, partners, service providers, and customers and they have provided input on product and manufacturability requirements

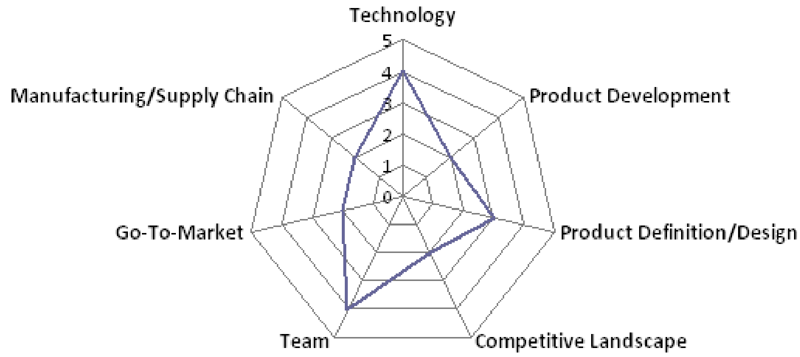

Figure 17.27 – TRL&CRL fuselage noise abatement devices for turboprop aircraft

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

Technology & Commercialization Readiness Level Calculator

Profile	
Company/Organization Name:	SAFRAN Nacelles
Proposal Title:	SAS with 3-D spiral cell
Product/Innovation Description:	SAS of complicated configurations are the possible solution of absorbing the sound of low frequencies with simultaneous reduction of the thickness of the nacelle panels

Technology Readiness Level 3

Commercialization Readiness Level 2

Category	Answer
Technology	Preliminary testing of technology components has begun, and technical feasibility has been established in a laboratory environment
Product Development	Pilot scale product/system has been tested in the intended application(s)
Product Definition/Design	Mapping product/system attributes against customer needs has highlighted a clear value proposition
Competitive Landscape	Primary market research to prove the product/system commercial feasibility has been completed and basic understanding of competitive products/systems has been demonstrated
Team	Balanced team with technical and business development/commercialization experience running the company with assistance from outside advisors/mentors
Go-To-Market	Initial business model and value proposition have been defined
Manufacturing/Supply Chain	Potential suppliers, partners, and customers have been identified and mapped in an initial value chain analysis

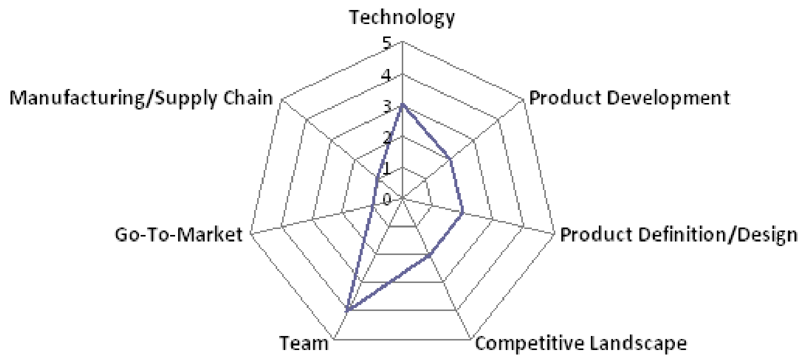

Figure 17.28 – TRL&CRL of SAS with 3-D spiral cell

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

Technology & Commercialization Readiness Level Calculator

Profile	
Company/Organization Name:	Institut für Fluid- und Thermodynamik (Michael Kohlhaas, Konrad Bamberger, Thomas Carolus)
Proposal Title:	Fan blade with additional air mass blowing into the aerodynamic trail
Product/Innovation Description:	Specially profiled blade with air blowing along the trailing edge provides the reduce in acoustic pressure level of 10-20 dB

Technology Readiness Level 3

Commercialization Readiness Level 1

Category	Answer
Technology	Preliminary testing of technology components has begun, and technical feasibility has been established in a laboratory environment
Product Development	Pilot scale product/system has been tested in the intended application(s)
Product Definition/Design	Mapping product/system attributes against customer needs has highlighted a clear value proposition
Competitive Landscape	Secondary market research has been performed and basic knowledge of potential applications and competitive landscape have been identified
Team	No team or company in place (single individual, no legal entity)
Go-To-Market	Initial business model and value proposition have been defined
Manufacturing/Supply Chain	Potential suppliers, partners, and customers have been identified and mapped in an initial value chain analysis

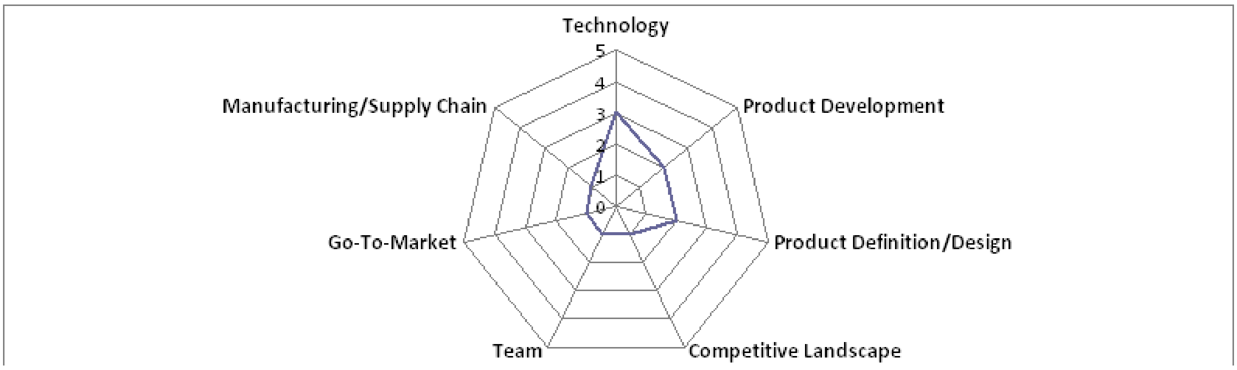

Figure 17.29 – TRL&CRL of fan (compressor) blades with additional air mass blowing into the aerodynamic trail

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

Technology & Commercialization Readiness Level Calculator

Profile	
Company/Organization Name:	Pratt & Whitney
Proposal Title:	Fan for engines series Pure Power Geared Turbofan (first generation)
Product/Innovation Description:	Minimization of fan acoustic emission is provided by blade shape, decrease in rotation speed (use of fan drive system)

Technology Readiness Level 9

Commercialization Readiness Level 9

Category	Answer
Technology	Laboratory scale integrated product/system demonstrates performance in the intended application(s)
Product Development	Product/system is in final form and has been operated under the full range of operating conditions and environments
Product Definition/Design	Product/system final design optimization has been completed, required certifications have been obtained, and product/system has incorporated detailed customer and product
Competitive Landscape	Full and complete understanding of the competitive landscape, target application(s), competitive products/systems, and market has been achieved
Team	Balanced team with all capabilities onboard (e.g. sales, marketing, customer service, operations, etc.) running the company with assistance from outside advisors/mentors
Go-To-Market	Supply agreements with suppliers and partners are in place and initial purchase orders from customers have been received
Manufacturing/Supply Chain	Full scale manufacturing and widespread deployment of product/system to customers and/or users has been achieved

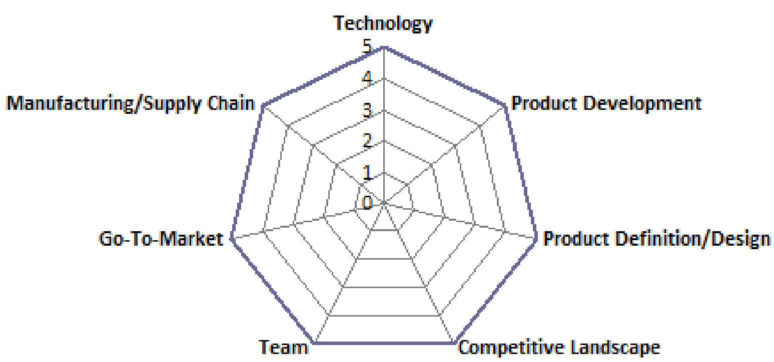

Figure 17.30 – TRL&CRL of the fan for Pure Power Turbofan engine series (first generation)

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

Technology & Commercialization Readiness Level Calculator

Profile	
Company/Organization Name:	Pratt & Whitney
Proposal Title:	Fan for engines series Pure Power Geared Turbofan (second generation)
Product/Innovation Description:	Minimization of fan acoustic emission in comparison with the first generation.

Technology Readiness Level 7

Commercialization Readiness Level 4

Category	Answer
Technology	Initial testing of integrated product/system has been completed in a laboratory environment
Product Development	Demonstration of a full scale product/system prototype has been completed in the intended application(s)
Product Definition/Design	Comprehensive customer value proposition model has been developed, including a detailed understanding of product/system design specifications, required certifications, and trade-
Competitive Landscape	Competitive analysis to illustrate unique features and advantages of the product/system compared to competitive products/systems has been completed
Team	Balanced team with all capabilities onboard (e.g. sales, marketing, customer service, operations, etc.) running the company with assistance from outside advisors/mentors
Go-To-Market	Partnerships have been formed with key stakeholders across the value chain (e.g. suppliers, partners, service providers, and customers)
Manufacturing/Supply Chain	Relationships have been established with potential suppliers, partners, service providers, and customers and they have provided input on product and manufacturability requirements

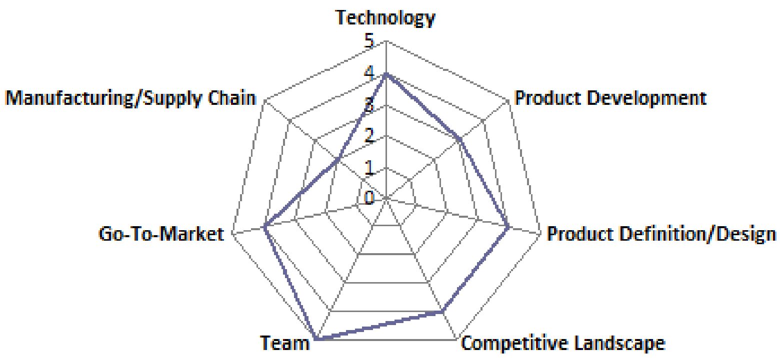

Figure 17.31 – TRL&CRL of the fan for engines series Pure Power Turbofan (second generation)

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

Technology & Commercialization Readiness Level Calculator

Profile	
Company/Organization Name:	General Electric
Proposal Title:	Fan for GEnx engines
Product/Innovation Description:	Composite fan blades with steel edge are designed by taking into account the improvement of aeroacoustic performance

Technology Readiness Level 9

Commercialization Readiness Level 9

Category	Answer
Technology	Laboratory scale integrated product/system demonstrates performance in the intended application(s)
Product Development	Product/system is in final form and has been operated under the full range of operating conditions and environments
Product Definition/Design	Product/system final design optimization has been completed, required certifications have been obtained, and product/system has incorporated detailed customer and product
Competitive Landscape	Full and complete understanding of the competitive landscape, target application(s), competitive products/systems, and market has been achieved
Team	Balanced team with all capabilities onboard (e.g. sales, marketing, customer service, operations, etc.) running the company with assistance from outside advisors/mentors
Go-To-Market	Supply agreements with suppliers and partners are in place and initial purchase orders from customers have been received
Manufacturing/Supply Chain	Full scale manufacturing and widespread deployment of product/system to customers and/or users has been achieved

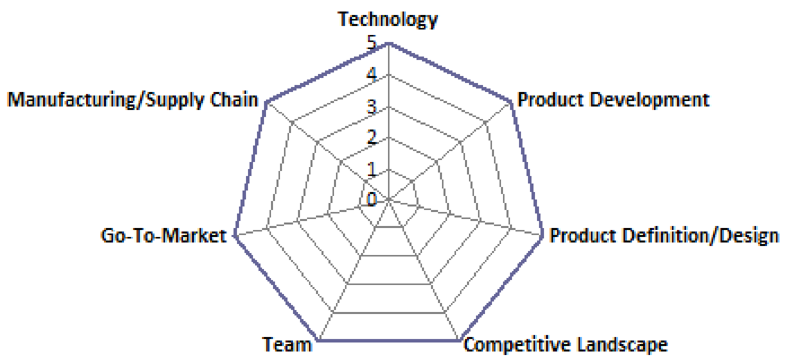

Figure 17.32 – TRL&CRL of the fan for GEnx engines

NYSERDA

Technology & Commercialization Readiness Level Calculator

Profile	
Company/Organization Name:	JSC «UEC-Aviadvigatel»
Proposal Title:	Fan blade of the PD-14 engine
Product/Innovation Description:	Wide-chord hollow titanium blade is designed by taking into account the decrease of aeroacoustic emission

Technology Readiness Level 9

Commercialization Readiness Level 8

Category	Answer
Technology	Laboratory scale integrated product/system demonstrates performance in the intended application(s)
Product Development	Product/system is in final form and has been operated under the full range of operating conditions and environments
Product Definition/Design	Product/system final design optimization has been completed, required certifications have been obtained, and product/system has incorporated detailed customer and product requirements
Competitive Landscape	Competitive analysis to illustrate unique features and advantages of the product/system compared to competitive products/systems has been completed
Team	Balanced team with all capabilities onboard (e.g. sales, marketing, customer service, operations, etc.) running the company with assistance from outside advisors/mentors
Go-To-Market	Supply agreements with suppliers and partners are in place and initial purchase orders from customers have been received
Manufacturing/Supply Chain	Products/systems have been pilot manufactured and sold to initial customers

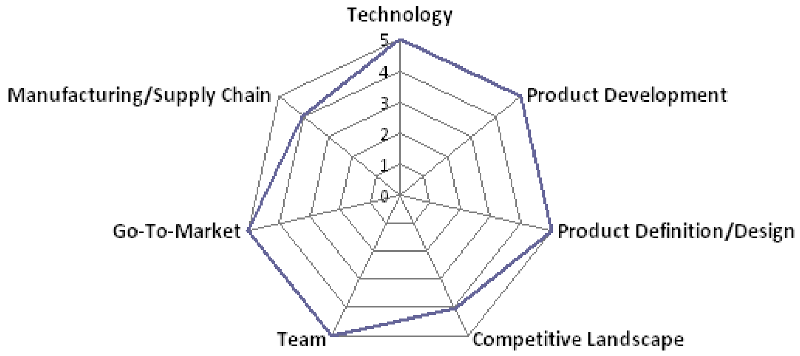

Figure 17.33 – TRL&CRL of fan blades of the PD-14 engine

Technology & Commercialization Readiness Level Calculator

Profile	
Company/Organization Name:	Central Institute of Aviation Motors (CIAM)
Proposal Title:	Acoustic performance of fan model with guide vanes
Product/Innovation Description:	Inclination of guide vanes (GV) is advanced technique of fan noise abatement. The influence of inclination of guide vanes in the direction of rotation and in the opposite direction is investigated. Model and numerical experiments are carried

Technology Readiness Level 3

Commercialization Readiness Level 2

Category	Answer
Technology	Preliminary testing of technology components has begun, and technical feasibility has been established in a laboratory environment
Product Development	Initial product/market fit has been defined
Product Definition/Design	Mapping product/system attributes against customer needs has highlighted a clear value proposition
Competitive Landscape	Primary market research to prove the product/system commercial feasibility has been completed and basic understanding of competitive products/systems has been demonstrated
Team	Balanced team with technical and business development/commercialization experience running the company with assistance from outside advisors/mentors
Go-To-Market	Customers/partners have been interviewed to understand their pain points/needs, and business model and value proposition have been refined based on customer/partner feedback
Manufacturing/Supply Chain	Relationships have been established with potential suppliers, partners, service providers, and customers and they have provided input on product and manufacturability requirements

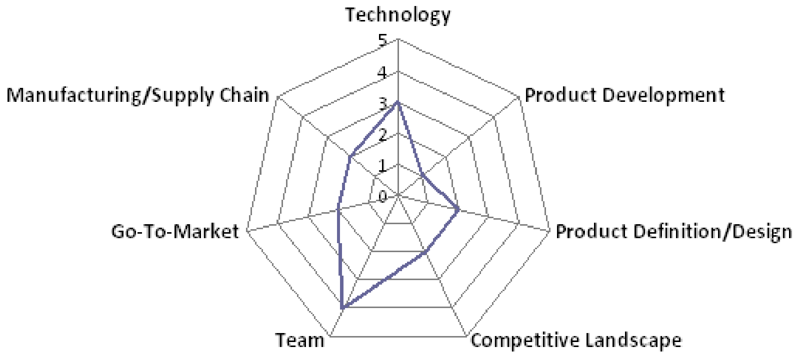

Figure 17.34 – TRL&CRL of the fan with inclined guide vanes

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

Technology & Commercialization Readiness Level Calculator

Profile	
Company/Organization Name:	Central Institute of Aviation Motors (CIAM)
Proposal Title:	Combined noise attenuator
Product/Innovation Description:	Combined covering comprises the sections of absorbing (honeycomb SAS) and jet elements

Technology Readiness Level 3

Commercialization Readiness Level 2

Category	Answer
Technology	Preliminary testing of technology components has begun, and technical feasibility has been established in a laboratory environment
Product Development	Pilot scale product/system has been tested in the intended application(s)
Product Definition/Design	Mapping product/system attributes against customer needs has highlighted a clear value proposition
Competitive Landscape	Primary market research to prove the product/system commercial feasibility has been completed and basic understanding of competitive products/systems has been demonstrated
Team	Balanced team with technical and business development/commercialization experience running the company with assistance from outside advisors/mentors
Go-To-Market	Initial business model and value proposition have been defined
Manufacturing/Supply Chain	Potential suppliers, partners, and customers have been identified and mapped in an initial value chain analysis

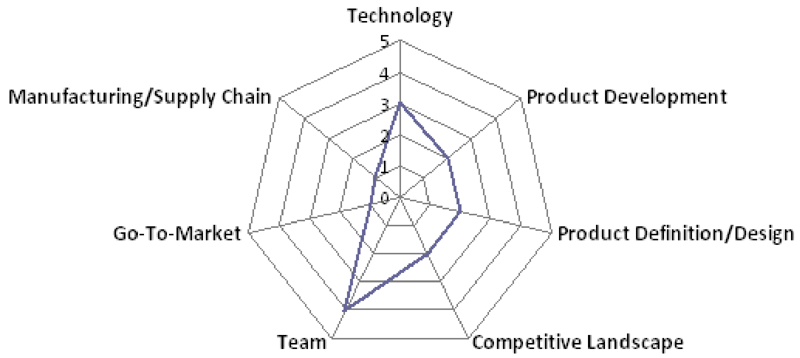

Figure 17.35 – TRL&CRL of combined noise attenuator

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

Technology & Commercialization Readiness Level Calculator

Profile	
Company/Organization Name:	Khristianovich Institute of Theoretical and Applied Mechanics SB RAS
Proposal Title:	Use of microjets in a supersonic underexpanded jet
Product/Innovation Description:	Use of microjets in a supersonic underexpanded jet in the jet nozzle of gas-turbine engine permits to reduce the acoustic pressure level

Technology Readiness Level	3
Commercialization Readiness Level	1

Category	Answer
Technology	Preliminary testing of technology components has begun, and technical feasibility has been established in a laboratory environment
Product Development	Initial product/market fit has been defined
Product Definition/Design	One or more initial product hypotheses have been defined
Competitive Landscape	Secondary market research has been performed and basic knowledge of potential applications and competitive landscape have been identified
Team	Solely technical or non-technical founder(s) running the company with no outside assistance
Go-To-Market	Initial business model and value proposition have been defined
Manufacturing/Supply Chain	Potential suppliers, partners, and customers have been identified and mapped in an initial value chain analysis

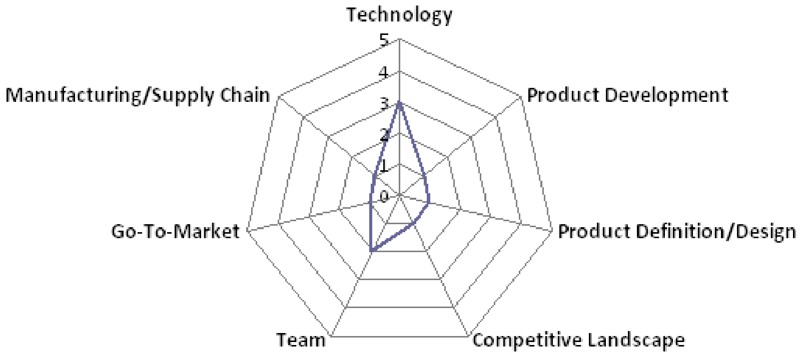

Figure 17.36 – TRL&CRL of the use of microjets in a supersonic underexpanded jet

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

Technology & Commercialization Readiness Level Calculator

Profile	
Company/Organization Name:	Central Institute of Aviation Motors (CIAM)
Proposal Title:	Integration of power plant and aircraft
Product/Innovation Description:	Multiobjective optimization of power plant parameters for aircraft of different purpose and flight speeds according to optimality criteria: performance, fuel efficiency, carrier cost, life cycle cost, environmental performance

Technology Readiness Level	**2**
Commercialization Readiness Level	**2**

Category	Answer
Technology	Applied research has begun and practical application(s) have been identified
Product Development	Initial product/market fit has been defined
Product Definition/Design	Mapping product/system attributes against customer needs has highlighted a clear value proposition
Competitive Landscape	Primary market research to prove the product/system commercial feasibility has been completed and basic understanding of competitive products/systems has been demonstrated
Team	Balanced team with technical and business development/commercialization experience running the company with assistance from outside advisors/mentors
Go-To-Market	Partnerships have been formed with key stakeholders across the value chain (e.g. suppliers, partners, service providers, and customers)
Manufacturing/Supply Chain	Potential suppliers, partners, and customers have been identified and mapped in an initial value chain analysis

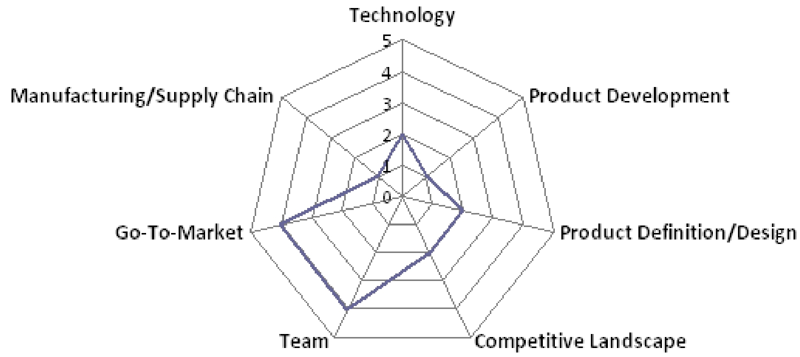

Figure 17.37 – TRL&CRL of power plant and aircraft integration

The results of the analysis of readiness level of technologies (TRL) and commercialization readiness level are presented in table 17.5. In addition, the location of reviewed technology development is presented in the table.

No	Technologies	Developer	TRL	CRL
1	Composite fan blade (Rolls-Royce)	EU	8	4
2	OPEN ROTOR propfan	EU	6	4
3	Fan blade designed by Safran Company	EU	7	4
4	Device for noise reduction in the airframe of the aircraft with turboprop engines	EU	6	2
5	Sound absorbing structure (SAS) with 3D spiral cell of Safran Nacelles	EU	3	2
6	Compressor fan blade with blowing out extra air mass into aerodynamic wake	EU	3	1
7	Fan of Pure Power Turbofan series engines (the first generation)	USA	9	9
8	Fan of Pure Power Turbofan series engine (the second generation)	USA	7	4
9	Fan of GEnx series engines	USA	9	9
10	PD-14 fan	RF	9	8
11	Fan with raked blades of the outlet straightener	RF	3	2
12	Combined noise suppressor	RF	3	2
13	Use of micro-jets in a supersonic under-expanded jet	RF	3	1
14	Integration of power plant and aircraft	RF	2	2

Table 17.5 - The results of the analysis of TRL/CRL technologies

Third Section Conclusions

Evaluation model of technologies readiness level – TRL provides an opportunity for developers and customers to control progress of their development and selection of technologies that are maximum ready for system integration and industrial introduction of technologies.

The following parameters are important for evaluation of technology feasibility: organizational readiness, risks and commercialization readiness that are evaluated by model - Commercialization Readiness Level CRL.

The results of conducted evaluation allow to conclude that for the near future (to 2025) reviewed technologies are characterized with 6...9 readiness levels (TRL) (1 through 8 technologies) 4...9 levels of market readiness and commercialization (CRL) (1 through 7 technologies).

For the long term they are characterized with 2...3 levels of readiness (TRL) (9 through 14 technologies) and 1...2 levels of market readiness and commercialization (CRL) (7 through 14 technologies).

Therefore, only 7-8 technologies from the reviewed ones hold promise of technological and commercial readiness for realization in up to 2025-2030. 4 technologies among them are being developed in the European Union countries.

17.4. Analysis of completion of SRIA tasks under investigation

ACARE has developed strategic agenda of research and innovation (Strategic Research & Innovation Agenda (SRIA)) for solution of difficult tasks set forth in Flightpath 2050. Researches and innovations in aviation are the key to future mobility and prosperity as well as to problems of environment and energy engineering.

The table 17.6 presents the analysis of the projects according to SRIA tasks of the European companies, what TRL level has been achieved and what is a slippage (according to SRIA table).

SRIA tasks	Program, project title	Duration of the project	Technology short description	TRL, year	Slip-page as for the SRIA table
1. Noise shielding, e.g. acoustic liners and insulation for UHBR ratio engines and high speed turbines and lean burn combustion systems.	Clean Sky, ALEP	2008-2017	SAS for leading edge of engine nacelle	TRL 6, 2010	-
	FP7-JTI, HOSTEL	2012-2014	SAS for engine hot section (turbine) at temperatures 700°C	TRL 4-6, 2014	-
	FP7-JTI, ALTD	2011-2016	SAS for input system. The basis for them is technology of laser micro perforation	TRL 6, 2016	-
	H2020-EU.3.4.5.5. - ITD Engines, SALUTE	2018-2022	SAS for UBPR, they are to absorb sound on lower frequencies	TRL 4, 2022	2 years
2. Adaptive/active noise control - variable/morphing structures (e.g. fan blades, nozzles).	FP7-TRANSPORT, FLOCON	2008-2012	4 technologies for reduction of broadband noise of fans: wave-shaped leading and tailing edge, fixture miniflap in blades of a fan, adjustment of aerodynamic wake of blowing methods	TRL 4, 2012	-
	FP7-JTI	2008-2012	Two methods of noise reduction at CROR vanes: active method of reduction of wake behind	TRL 4-6, 2012	-

			the first raw of vanes by means of dielectric barrier discharge (DBD) and porous surface of vanes		
3. Low noise propellers design and technology.	FP7-JTI, IDOHAP	2010-2011	Key design technology was developed for CROR model for tests in wind tunnel, the first stage had 11 vanes, the second stage had 9 vanes	TRL 4-6, 2011	-
	Clean Sky 2, «Business aviation / Short range regional Turboprop Demonstrator»	2015-2020	New low-noise propeller for Integrated Power Plant System (IPPS)	TRL 4-6, 2020	-
4. Low noise fan blade for UHBR engines including open rotor.	FP6-AEROSPACE, VITAL	2005-2010	1. Contra-rotating fan: increase of efficiency by 1–2% and reduction of noise level by 3.5–4%. 2. Fan with direct drive of classical layout: reduction of fan noise level by ~6 EPN dB; increase of efficiency by 2%; reduction of fan mass by 30%	TRL 5-6, 2010	-
	FP7-TRANSPORT, DREAM	2008-2012	CROR fan with enhanced acoustic characteristics	TRL 4-6, 2012	-
	FP7-JTI, ENITEP	2012-2016	Mechanisms of CROR and airframe integration have been investigated within the range of Mach numbers 0.4...0.78 in order to reduce the noise from CROR engines	TRL 4-5, 2016	-
	Clean Sky, SAGE 3 Advanced Low Pressure System (ALPS)	2008-2017	Composite fan blade made of CTi (Carbon Titanium) for Advance and Ultra-fan engines, developed fan blade allowed to reduce the noise from 1 to 3	TRL 6, 2017	-

			EPNdB		
	FP7-TRANSPORT, ENOVAL	2013-2018	Engine (bypass ratio is up to 20) fan was developed. New structure peculiarities of low-pressure fan (optimization of vane form, amount of vanes, weight) allowed to reduce noise level up to 1.3 EPNdB and in total up to 9 EPNdB	TRL 5, 2018	-
	H2020-EU.3.4., TurboNoiseBB	2016-2020	Fans with low level of acoustic emission	TRL 4-5, 2020	-
	Clean Sky 2, Engines («Very High Bypass Ratio (VHBR) Large Turbofan demonstrator, 2014-2021» and «Very High Bypass Ratio (VHBR) Middle of Market Turbofan technology, 2014-2021»)	2014-2021	Fan for VHBR engine	TRL 5-6, 2021	1 year
	Clean Sky 2, Engines («Ultra-High Propulsive Efficiency (UHPE) demonstrator addressing Short / Medium Range aircraft market, 2014-2023»)	2014-2023	Fan for engine with ultra-high bypass ratio in the range 15-20	TRL 5-6, 2023	3 years
	Clean Sky, Clean Sky 2, Sage 2 CROR	2008-2017	CROR vanes. CROR engine the chapter of ICAO 14 on noise corresponds to it.	TRL 6, 2017	-
5. Noise reduction technologies for power gearbox systems.	FP7-JTI, OPTIMIZE	2014-2016	Optimization of structure of reduction gear with target function of reliability enhancement, noise reduction, compactibility	TRL 5-6, 2016	-

			enhancement and weight reduction.		
	FP7-JTI, Geared Turbofan Test Rig GTFTR	2013-2016	Epicyclic Power Gearbox is developed - Integral Drive System (IDS)	TRL 5-6, 2016	-
	Clean Sky GRA, Low-Noise Configuration	2008-2017	Concepts of new reduction gears aimed at noise reduction	TRL 5-6, 2017	-
	Clean Sky, SAGE 4	2008-2017	Light improved reduction gear with enhanced acoustic characteristics	TRL 5-6, 2017	-
	Clean Sky 2, Engines, Business aviation / Short range regional Turboprop Demonstrator	2015-2020	Development and integration of a reduction gear for Integrated Power Plant System (IPPS)	TRL 5-6, 2020	-
	H2020-EU.3.4.5.5. - ITD Engines, HILOGEAR	2017-2020	New materials and bearings are developed to assure optimal operation of IDS reduction gear	TRL 5-6, 2020	-
6. Fixed geometry intake, bypass and exhaust duct optimisation, extension of Treated Area.	FP7-JTI, TILTOP	2010-2011	Methodology is developed for optimization of inlet and outlet systems of engine nacelle of the aircraft engine	TRL 4-5, 2011	
	FP7-TRANSPORT, COBRA	2013-2017	The increase of bypass ratio of bypass engines with low-pressure fan up to 15-25 has been investigated in order to assure noise reduction	TRL 5-6, 2017	
7. Develop high fidelity CAA noise modelling capability and integrate into design optimisation capability at system and subsystem level (near and far field).	FP6-AEROSPACE, PROBAND	2005-2008	Method of prediction of wide-band noise for UHBR fans is developed	2008	-
	FP7-JTI, Flight-Noise-II	2011-2014	Computer code that is able to predict aircraft noise from turboprop aircraft in order to optimize aircraft route for minimization of acoustic	2014	-

			emission		
	Clean Sky, Systems for Green Operations	2008-2017	FLIGHT program complex, noise modelling in near field and far field	2017	-
	H2020-EU.3.4, TurboNoiseBB	2016-2020	Development of experimental facilities and method of prediction of wide-band noise of fans	2020	-
	H2020-EU.3.4.5.1., SCONE	2017-2020	It is focused on development of "quite" CROR and UHBR engines. Creation of enhanced statistical data of turbulence for use in semi analytic models with implementation of high-precision CFD methods, provision of proved high-precision methods for calculation of direct wide-band noise and enhancement of existing analytic models	2020	-

Table 17.6 - Analysis of projects according to SRIA tasks of the European companies

Analysis of data that are collected in the table shows that researches are being conducted in connection with all reviewed SRIA tasks and we can tell that European companies are in the lead concerning all reviewed SRIA tasks.

However, it should be mentioned that concerning Task 1 (Noise protection, for example, acoustic laps/inserts (SAS) and isolation for engines with UHBR (ultra-high bypass ratio) and high-speed turbines and systems of combustion of depleted fuel) in Russia researches are conducted devoted to creation of combined noise suppressors of fans and definition of rational place of their installation in order to reduce the noise, the European companies do not consider such concepts. Besides, the European companies have been developing SAS for engine hot section at the temperatures up to 700 °C, at the same time NASA have developed SAS that can be used at temperatures up to 1000°C..

In addition, it should be mentioned that in the Russian Federation and in the USA the full-scale researches are being conducted concerning Task 2 (adaptive/active control of noise – changeable/changing structures (for example, fan blades, nozzles).

In the Russian Federation various research programs study advanced methods of reduction of noise of reaction jet. For example, activities connected with research of active control over acoustic characteristics of reaction jet by means of micro-jets. As research results have shown, combination of active control over noise of reaction jet and application of chevron nozzles will allow to reduce the level of sound pressure of the reaction jet. Also methods of liquid injection, use of skewed nozzle, use of micro-jets, high-frequency excitation are being researched. All these methods have potential possibilities for reduction of noise by 1...2 EPN dB at run-out and climb.

The USA also actively develops adaptive/active control of noise – changeable/changing structures in the blades of fan and nozzle. As part of Quit Technologies Demonstrator 2 program, engine nacelles were developed with seamless inlet section and chevron nozzle made of form memory material. Use of developed technology allows to reduce takeoff noise level by ~3–4 dB and improve specific fuel consumption in the conditions of cruise flight by -1%, the technology is implemented in B777 aircraft with GE90 turbofan bypass engine. The system of active noise control is planned to be used for reduction of noise level. It includes acoustic resonators installed on blades of outlet straightener of the fan and device based on MEMS-technology. It allows reducing the noise level in the source by ~50–60%.

As part of Quiet Aircraft Technology (QAT) Program (since 2001), "revolution" technologies have been developed for the next generation of engines for A/C of different purpose in the wide range of flight speed. Within the scope of program, the main attention was paid to the researches of power plants for passenger aircraft. As a result, a reduction of noise by -20 EPN dB in relation to norms of ICAO Chapter 3 was achieved.

Within the scope of Quiet Aircraft Technology (QAT) Program, the following technologies have been investigated:

– Active control over frictional boundary layer on fan blades (blowing of additional air mass through cutting edge).
– Installation of acoustic over-rotor devices. The test results have shown that such concept provides for noise level reduction by ~3–4 dB.
– Installation of splitter in the channel behind the fan. This method allows reducing noise level in the downward flow direction behind the stage of the fan due to installation of additional acoustic surface. Results of test of one of the variants of such method in wind tunnel have shown that if the form and installation place of a splitter are chosen correctly, the noise level reduction will be up to ~1.5 dB, but in such event the loss of thrust that is generated by bypass flow can be up to -1%.
– Installation of Helmholtz resonators ("soft" blades of the straightener). This concept consists in the fact that cavities are made on the variable stator vanes with Helmholtz resonators installed in them, these resonators dampen pressure pulsations on the surface of the blades. The results of tests of low-frequency fan model have shown that reduction of noise level in the wide range of frequencies can make up to ~1.5 dB.

Fourth Section Conclusions

The researchers are being conducted in connection with all reviewed SRIA tasks (Challenge 3. Protecting the environment and energy supply), 3.1: Develop air vehicles of the future: evolutionary steps. Key element: Propulsion. Breakdown level 1: Reduce aircraft noise associate with the propulsive system), and we can say that European companies are in the lead concerning all reviewed SRIA tasks.

Cooperation with the Russian Federation and the USA with respect to active methods of noise control and creation of effective SAS will be rather useful for ACARE goals achievement.

17.5. Forecast and recommendations

Clean Sky 1 included technologies and procedures that would reduce perceived noise emissions by 65% compared to a typical new aircraft of 2000. One of the goals of the Clean Sky 2 initiative is to reduce noise by 20-30% compared to modern aircraft that have been in service since 2014.

Clean Sky 2 initiative (2014-2024), part of the EU Horizon 2020 program, a joint event between the European Commission and the European aviation industry. The Clean Sky 2 initiative builds on the original Clean Sky 1 (2008-2017) and contributes to the achievement of Flightpath 2050 environmental targets set by the Advisory Council for Aeronautics Research in Europe (ACARE).

Connecting the aviation industry, small and medium-sized enterprises, research centres and academia, Clean Sky 2 contributes to the achievement of innovative results, and also strengthens European cooperation in the aviation industry, global leadership and competitiveness. Clean Sky 2 has a total budget of € 4 billion and currently contains over 600 unique entities from 27 countries.

Clean Sky 2 expects to develop innovative, advanced technologies to create more efficient aerodynamic wings, improved and lighter designs, more efficient engines, including new areas of hybridization and electrification, advanced control, propulsion and guidance systems (including enhanced digitization), completely new aircraft configurations and a more sustainable aircraft life cycle. The scope of the program includes large regional and commuter aircraft as well as helicopters.

The program is aimed at accelerating the introduction of new technologies in the period 2025-2035. By 2050, 75% of the global fleet that is currently in operation will be replaced by aircraft that can use Clean Sky 2 technologies. Direct economic benefits are estimated at € 350-400 billion and related indirect benefits of around € 400 billion [101].

Table 17.7 lists some of the most recent US and European initiatives up to 2020-2025, along with their respective noise reduction targets.

Initiative (project)	Noise reduction targets
NextGen Continuous Lower Energy, Emissions and Noise (CLEEN)	Certified aircraft technology that reduces noise levels by 10 dB (30 dB in total) compared to subsonic jet technology of 1997.
NASA Subsonic Fixed Wing (SFW)	Conventional (2012-2015) (total lower than Stage 3): -42 dB. Hybrid Wing (2018-2020) (total lower than Stage 3): -52 dB
Advisory Council for Aeronautics Research in Europe (ACARE)	Reduce perceived noise by half (from 2000 to 2020) (interpreted as -10 EPNdB / operation)
NASA Quiet Aircraft Technology (QAT)	Reduce the perceived noise exposure of the future aircraft by half (10 dB) of today's subsonic aircraft (1997) within 10 years and by three quarters (20

	dB) within 25 years

Table 17.7 - US and European initiatives up to 2020-2025 [102].

Research objectives, by their nature, tend to be more aggressive than actually realizing of technological advantage as the technology advances in the product development process. In addition, the time required to fully integrate a technology almost always exceeds initial estimates.

Figure 17.38 shows the trends in the achievement of noise reduction targets compiled by experts [102].

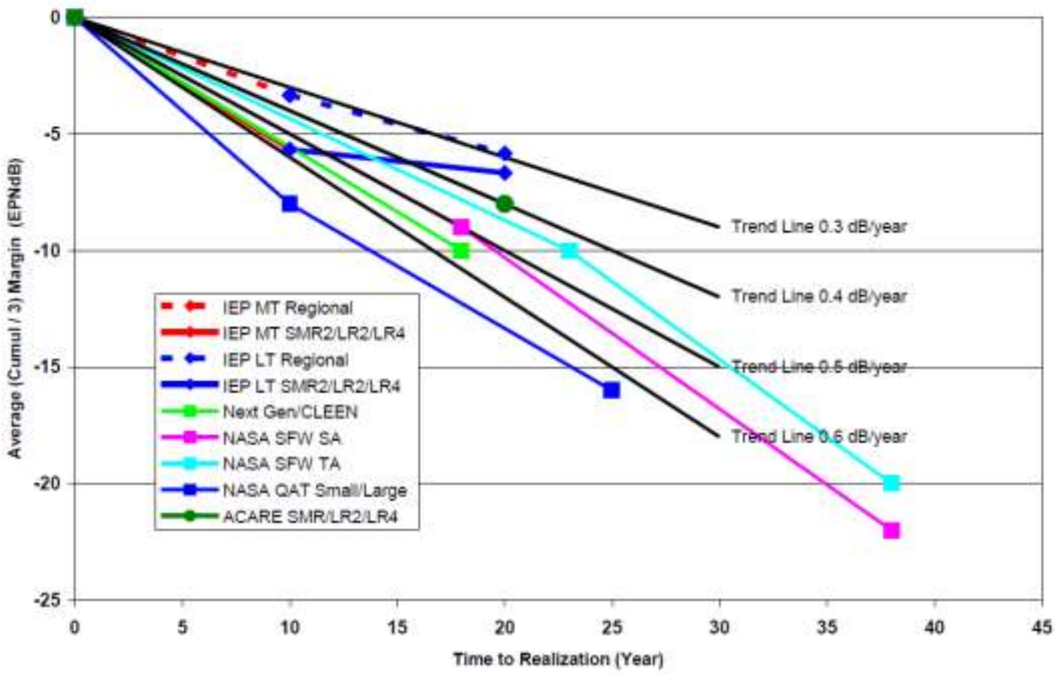

Figure 17.38 - Trends in meeting noise reduction targets

The average noise reduction margin is presented as a function of the time taken to achieve these objectives/tasks. The presented comparison results are made in TRL 6, as all published research objectives are specified in TRL 6. In addition, objectives are specified as the average of three certification scores or the cumulative value divided by three. There are both similarities and differences between the IEP projections and the study objectives. Whereas the regional IEP aircraft targets are in line with the historical trend of 0.3 dB / year, the medium-term (10 years) IEP targets for the remaining three aircraft classes show a more aggressive trend in comparison with trends in the study objectives. However, the IEP target goes beyond the medium term. Overall, over a 20-25 year period, the average noise abatement benefit assessed by the IEP and established by the study objectives is nearly the same within 3 EPNdB (9 EPNdB total). The objectives of the IEP are much closer to those of ACARE than those of NASA's programs, which are more aggressive. This may be because NASA programs assume a different architecture [102].

For all SRIA tasks considered (Challenge 3. Protecting the environment and energy supply), 3.1: Develop air vehicles of the future: evolutionary steps. Key element: Propulsion. Breakdown level 1: Reduce aircraft noise associate with the propulsive system) in Europe, research and technologies are being brought up to TRL 5-6, which makes it possible to conclude that the development and implementation of these technologies by 2025-2030 will allow European companies to achieve the ACARE goal.

Both the CROR engine and the ultrahigh bypass geared turbofan have the potential to significantly reduce fuel consumption and hence operating costs.

To further reduce the sound pressure level of ultrahigh bypass geared turbofans, it is necessary to focus on deeper and more versatile development of adaptive, active, passive methods of noise reduction for fan blades and jet nozzle.

The technologies that have been developed permit to conclude that today an ultrahigh bypass geared turbofan has a sound pressure level significantly lower than a CROR engine. At the same time, as shown by tests, the aircraft with CROR engines will comply with ICAO Chapter 14 standards.

It is also obvious that the CROR engine has a higher efficiency than an ultra-high bypass turbofan. Thus, it can be concluded that further research into improving acoustic performance will be associated with the development of the CROR engine.

It should be noted that, having completely exhausted the reserves for optimizing the shape of the blades, research aimed at a deeper study of active, adaptive, passive noise reduction methods, including boundary layer control, may be in great demand. Morphing technologies are already beginning to be developed by European companies for helicopter blades. Perhaps the results obtained can be used as a basis for the development of the Morphing concept of technologies for the CROR engine blades.

Integration with the aircraft will play an important role in reducing the noise of the CROR propulsion system. Work in this direction is already underway.

Figure 17.39 presents the possibilities of technologies complex to reduce noise for engines of the Open Rotor type.

Figure 17.40 presents the possibilities of technologies complex to reduce noise for Rolls-Royce engines for the period up to 2050.

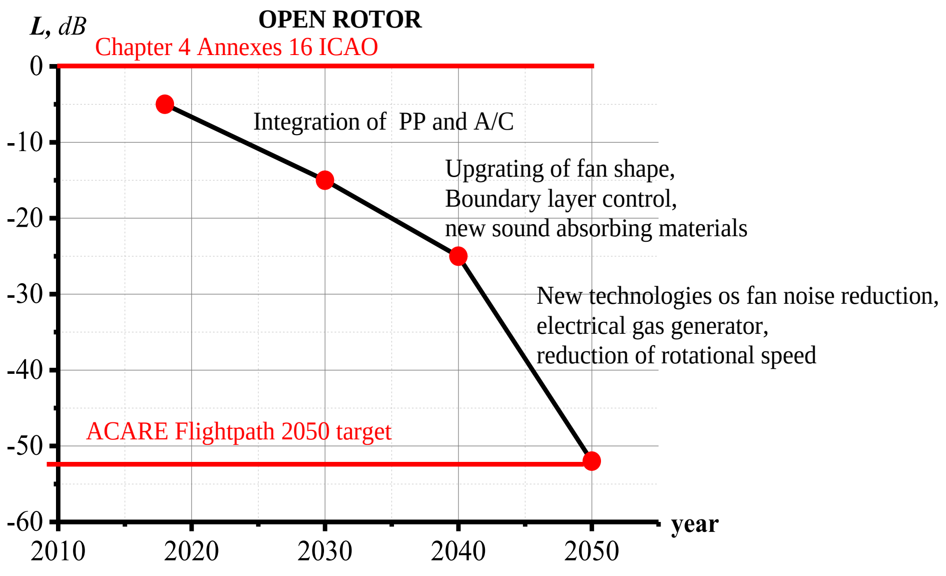

Figure 17.39 – The possibilities of technologies complex to reduce noise for engines of the Open Rotor type.

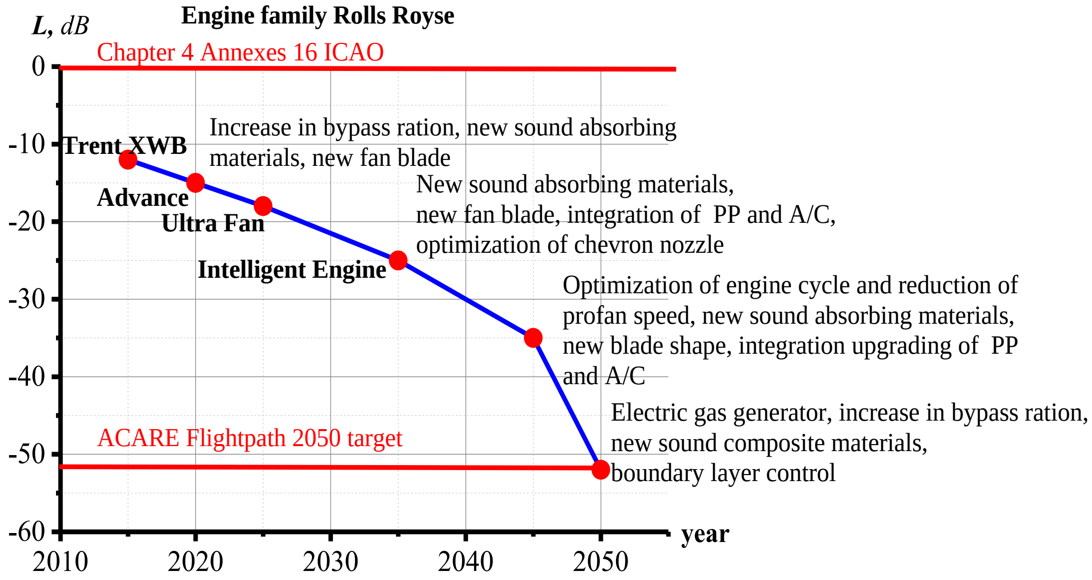

Figure 17.40 – The possibilities of technologies complex to reduce noise for Rolls-Royce family engines

Also, research aimed at a deeper understanding of the noise interaction of the rows of CROR fan blades and research dedicated to the creation of more advanced program codes for versatile modelling of noise in the source, in the near and far fields will remain relevant.

Fifth Section Conclusions

The introduction of such technologies as effective SAS, active (adaptive) noise control, optimal fan blade shapes made of new composite materials, low-noise propeller blades, improved reduction gears, improved input and output devices, reliable noise prediction methods will help achieve ACARE goal of noise reduction.

In the future, there will be improvements in technologies to reduce the CROR engine, this is due to its higher efficiency compared to UHBR, and poorer acoustic performance compared to UHBR.

In addition, the technologies of active (adaptive), passive noise control are likely to be further developed and program codes for versatile modelling of noise in the source, in the near and far fields, will be improved.

General conclusions

Acoustic perfection is one of the important requirements of modern and advanced aircraft engines.

The paper provides an overview of pan-European projects, national projects of European countries, as well as research outside Europe regarding 7 SRIA tasks to reduce aircraft engine noise - Challenge 3. Protecting the environment and energy supply, 3.1: Develop air vehicles of the future: evolutionary steps. Key element: Propulsion. Breakdown level 1: Reduce aircraft noise associate with the propulsive system.

This review has shown that research is being actively carried out in Europe and outside Europe to reduce power plant noise.

The paper provides a comparative analysis of the achieved level of technology in Europe with competing countries in relation to the implementation of SRIA tasks to reduce aircraft engine noise.

For all SRIA tasks considered, research is underway in Europe and technologies are brought to TRL 5-6, which permits to conclude that the development and implementation of these technologies by 2025-2030 will allow European companies to achieve the ACARE goal.

Achieving the ACARE noise reduction goal is possible with the introduction of technologies such as:

- effective SAS,
- active (adaptive) noise control,
- optimal shape of fan blades made of new composite materials,
- low noise propeller blades,
- improved reduction gears,
- improved inlet and exhaust sections,
- reliable methods for noise prediction.

Both the CROR engine and the geared ultrahigh-bypass turbofan have the potential to significantly reduce fuel consumption and hence operating costs. In the future, there will be improvements in technologies to reduce the CROR engine, this is due to its higher efficiency compared to UHBR, and poorer acoustic performance compared to UHBR.

In addition, the technologies of active (adaptive), passive noise control are likely to be further developed and program codes for versatile modelling of noise in the source, in the near and far fields, will be improved.

Collaboration with the Russian Federation and the United States on active noise control techniques and effective SAS will be highly beneficial in achieving ACARE goals.

References

[1] Zante D. V., Elliot D.M. Acoustics Considerations for Propulsion Airframe Integration. ISABE-2019-24443, 2019. 16 p.: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/ 20190032075.pdf

[2] Glenn Research Center. NASA: https://www.nasa.gov/centers/glenn/images/content/ 83522main_fs003_fig3.gif

[3] Achievements Timeline. Clean Sky: https://www.cleansky.eu/achievements-timeline

[4] Large 3-shaft Demonstrator – Aeroengine intake acoustic liner technology development. CORDIS: https://cordis.europa.eu/article/id/157727-acoustic-liners-for-quieter-aeroengines

[5] Smart Acoustic Lining for UHBR Technologies Engines. CORDIS: https://cordis.europa.eu/project/id/821093

[6] Aeroacoustics Methods for Fan-Noise Prediction and Control. CORDIS: https://cordis.europa.eu/project/id/AER30053

[7] Integration of a Hot StrEam Liner into the Turbine Exit Casing (TEC). CORDIS: https://cordis.europa.eu/article/id/157608-suppressing-noise-of-turbofan-engines

[8] Delfs J.W., Appel Ch., Bernickey P., Blechz Ch., Blinstrubx J., Heykena C., Kumary P., Kutscherk K., Lippitz N., Lummer M., Rossian L., Savoni L. Aircraft and technology for low noise short take-off and landing. 35th AIAA Applied Aerodynamics Conference: Proceedings of Conference, 5-9 June 2017 y. Denver, Colorado.

[9] Versaevel M., Moreau L., Lacouture E. Folded spiral-shaped cavities for nacelle acoustic liners: Impedance and attenuation modelling and comparison to experimental results. Greener Aviation Conference: Proceedings of Conference, 11-13 October 2016y. Brussels, 2016. ID 23.

[10] Госконтракты. ЦАГИ: http://www.tsagi.ru/goscontracts/

[11] Халецкий Ю. Д. Эффективность комбинированных глушителей шума Акустический журнал. 2012. Т.58, №4. С. 556–562.

[12] Солонин В.И., Халецкий Ю.Д. Пути достижения перспективных требований к шуму самолетов гражданской авиации. Экологические проблемы авиации. 2010. С. 11-38

[13] Compact, Lightweight, CMC-Based Acoustic Liner. NASA: https://technology.nasa.gov/patent/LEW-TOPS-61

[14] Adaptive and Passive Flow Control for Fan Broadband Noise Reduction. CORDIS:: https://cordis.europa.eu/project/id/213411/reporting

[15] Design of innovative CROR blade and pylon. CORDIS: https://cordis.europa.eu/project/id/255878

[16] Polacsek C., Barrier R., Kohlhaas M., Carolus T., Kausche P., Moreau A., Kennepohl F. Turbofan Interaction Noise Reduction Using Trailing Edge Blowing: Numerical Design and Assessment and Comparison with Experiments. AerospaceLab Journal. 2014. Issue 7. P. AL07-03 (doi : 10.12762/2014.AL07-03)

[17] Szoke M., Elsahhar W., Azarpeyvand M. Aerodynamic noise reduction using active flow control techniques. Greener Aviation Conference: Proceedings of Conference, 11-13 October 2016y. Brussels, 2016. ID 191.

[18] Suman A., Fortini A., Aldi N., Pinelli M., Merlin M. Analysis of the Aerodynamic and Structural Performance of a Cooling Fan with Morphing Blade. International Journal of Turbomachinery, Propulsion and Power. 2017. V. 2(2). №7. 11 p.

[19] Fortini A., Suman A., Aldi N., Merlin M., Pinelli M. A Shape Memory Alloy-Based Morphing Axial Fan Blade,Part I: Blade Structure Design and Functional Characterization. Journal of Engineering for Gas Turbines and Power. 2016. V. 138. №2. 8 p.

[20] Monner H. P., Huxdorf O., Riemenschneider J., Keimer R. Design and manufacturing of morphing fan blades for experimental investigations in a cascaded wind tunnel. Proceedings of 23rd AIAA/AHS Adaptive Structures Conference: Proceedings of Conference, 5-9 January 2015 y, Kissimmee, Florida, 13 p. (doi: 10.2514/6.2015-0790)

[21] Kohlhaas M., Carolus T.H. Acoustic minimization of rotor-stator interaction noise of axial fans by trailing-edge blowing Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition : Proceedings of Conference,16-20 June 2014 y. Düsseldorf, Germany. V02AT41A002 (doi: 10.1115/GT2014-25113)

[22] Губанов Д. А. Влияние микроструй и акустическое излучение сверхзвуковой недорасширеной струи: дис. канд. физ.-мат. наук: 01.02.05 / ИТПМ СО РАН. Новосибирск, 2014. 140 с.

[23] Рыбинская Л.А., Бульбович Р.В., Кычкин В.И. Эффективность методов снижения шума турбулентных струй. Вестник ПНИПУ. Аэрокосмическая техника. 2017. № 48. С.104-118 (doi: 10.15593/2224-9982/2017.48.10)

[24] A Boeing-led team is working to make quiet jetliners even quieter. Boeing: https://www.boeing.com/news/frontiers/archive/2005/december/ts_sf07.html

[25] Ultra-Efficient Engine Technology (UEET) Program. NASA: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050195882.pdf

[26] NASA Ultra Efficient Engine NASA Ultra Efficient Engine Technology Project Overview. NASA: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040182400.pdf

[27] Green engine technology. JAXA: http://www.aero.jaxa.jp/eng/research/ecat/greenengine/

[28] Doroshenko E., Tereshchenko Y., Lastivka I., Tereshchenko Y. Calculation of sound power level of tandem axial fan. Eastern European Journal of Enterprise Technologies. 2017. V. 6, N. 5–90. P. 8–12. (doi: 10.15587/1729-4061.2017.114038).

[29] 17N. Engines Clean Sky. Clean Sky: https://www.cleansky.eu/engines

[30] Study of Noise and Aerodynamics of Advanced Propellers. CORDIS: https://cordis.europa.eu/project/id/AER20038

[31] Innovative Design of Hubs and Propellers. CORDIS: https://cordis.europa.eu/project/id/255782

[32] Zhang X. Aircraft noise and its nearfield propagation computations. Acta Mechanica Sinica. 2012. V. 28. № 4. P. 960–977. doi: 10.1007/s10409-012-0136-.

[33] Lieser J.A., Lohmann D., Rohardt C.-H. Aeroacoustic design of a 6-bladed propeller. Aerospace Science and Technology. 1997. V. 1. N. 6 P. 381–389. doi:10.1016/S1270-9638(97)90012-2

[34] Arena M., De Fenza A., Di Giulio M., Paonessa A., Amoroso F. Progress in studying passive and active devices for fuselage noise reduction for next generation turboprop. Greener Aviation Conference: Proceedings of Conference, 11-13 October 2016y. Brussels, 2016. ID 186.

[35] Аэроакустика. ЦАГИ: http://www.tsagi.ru/research/aeroacoustics/

[36] В ЦАГИ завершены испытания модели фюзеляжа с хвостовым винтом. Деловой авиационный портал: http://www.ato.ru/press-releases/v-cagi-zaversheny-ispytaniya-modeli-fyuzelyazha-s-hvostovym-vintom?sea=8852

[37] Мошков П. А., Самохин В. Ф. Оценка влияния числа лопастей и диаметра на шум воздушного винта. Вестник Самарского университета. Аэрокосмическая техника, технологии и машиностроение. 2016. Т.15. №3. С. 25-34. doi: 10.18287/2541-7533-2016-15-3-25-34

[38] Мошков П. А. О направленности акустического излучения винтомоторных силовых установок. Вестник Уфимского государственного авиационного технического университета. 2017. Т. 21. № 1 (75). С. 118–127

[39] Самохин В. Ф., Мошков П. А. Экспериментальное исследование акустических характеристик силовой установки самолета «Ан-2» в статических условиях. Труды МАИ. 2015. № 82. С.1–25.: https://mai.ru/upload/iblock/3cb/samokhin_moshkov_rus.pdf

[40] Самохин В. Ф., Мошков П. А. Акустические характеристики легкого винтового самолета с двигателем внутреннего сгорания. Труды МАИ. 2012. № 57. С.1-12.: http://www.trudymai.ru/upload/iblock/8dd/akusticheskie-kharakteristiki-legkogo-vintovogo-samoleta-s-dvigatelem-vnutrennego-sgoraniya.pdf

[41] Scharpf D. F., Mueller T. J. An experimental investigation of the sources of propeller noise due to the ingestion of turbulence at low speeds. Experiments in Fluids. 1995. V. 18. Issue 4. P. 277–287. doi: 10.1007/BF0019509

[42] Gliebe P.R. Aeroacoustics in Turbomachines and Propellers — Future Research Needs. Unsteady Aerodynamics, Aeroacoustics, and Aeroelasticity of Turbomachines and Propellers. New York: Springer, 1993. P.619-642. doi: 10.1007/978-1-4613-9341-2_31.

[43] Nark D. M., Buning P. G., Jones W. T., Derlaga J. M. High-Lift Propeller Noise Prediction for a Distributed Electric Propulsion Flight Demonstrator. NASA: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170006070.pdf

[44] Wu Y., Ai Y., Ze W., Jing T., Song X., Chen Y. A Novel Aerodynamic Noise Reduction Method Based on Improving Spanwise Blade Shape for Electric Propeller Aircraft. International Journal of Aerospace Engineering. 2019. ID 3750451. 10 p.

[45] Yang L., Huang J. Y. M., Zhang Ch., Xiao Q. A numerical study of the effects of design parameters on the acoustics noise of a high efficiency propeller. Acoustical Physics. 2017. V. 63, № 6. P. 699–710. doi: 10.1134/S1063771017060033.

[46] Zimcik D.G. Active control of aircraft cabin noise. AVT 101 symposium on Habitability of Combat and Transport Vehicles: Noise, Vibration and Motion: Proceedings of Conference, 4 Octobre 2004 y. Prague, Czech Republic. RTO-MP-AVT-110 -20.

[47] Sustainable and Green Engines (SAGE). Clean Sky: https://www.cleansky.eu/sustainable-and-green-engines-sage

[48] Validation of improved turbomachinery noise prediction models and development of novel design methods for fan stages with reduced broadband noise. CORDIS: https://cordis.europa.eu/project/id/690714/reporting

[49] Engine Module Validators. CORDIS: https://cordis.europa.eu/project/id/604999

[50] Environmentally Friendly Aero Engine. CORDIS: https://cordis.europa.eu/project/id/12271

[51] Сградлев В.В. Оптимизация количества лопаток биротативной ступени вентилятора, с точки зрения уменьшения шума в самом источнике. Научный вестник МГТУ ГА. 2009. №147. С. 136-141.

[52] Validation of Radical Engine Architecture systems. CORDIS: https://cordis.europa.eu/project/id/211861

[53] Experimental and Numerical Investigation of Turbulent Boundary Layer Effects on Noise Propagation in High Speed Conditions. CORDIS: https://cordis.europa.eu/article/id/201317-quieter-open-rotor-aircraft

[54] Hildebrandt T., Thiel P., Albert S., Vilmin S. Applying an extended non linear harmonic method to a CROR configuration with emphasis on the acoustic signature. Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition: Proceedings of Conference, 16-20 June 2014 y. Düsseldor, Germany, V02AT41A001 (doi: 10.1115/GT2014-25061).

[55] Kröger, G., Schnell, R., Humphreys, N. D. 2012 Optimised Aerodynamic Design of an OGV With Reduced Blade Count for Low Noise Aircraft Engines. ASME Turbo Expo 2012: Turbine Technical Conference and Exposition. Volume 8: Turbomachinery, Parts A, B, and C, pages 407-418, Copenhagen, Denmark (doi:10.1115/GT2012-69459)

[56] Danner F., Kendall-Torry C. Effect of blade tip modifications for unducted propulsors on tip vortex-rotor interaction noise. ASME Turbo Expo 2014: Turbine Technical Conference and Exposition: Proceedings of Conference, 16-20 June 2014 y. Düsseldor, Germany, V02AT41A014 (doi: 10.1115/GT2014-27134).

[57] Silent flights: How owls could help make wind turbines and planes quieter. University of Cambridge: https://www.cam.ac.uk/research/news/silent-flights-how-owls-could-help-make-wind-turbines-and-planes-quieter.

[58] Belyaev I.V., Kopiev V.F., Medvedev Yu.V., Shur M.L., Travin A.K. Assessment of community noise for aircraft with open rotor engines based on numerical simulation. Greener Aviation Conference: Proceedings of Conference, 11-13 October 2016y. Brussels. ID 219.

[59] Замтфорт Б.С. Двигатель с открытым ротором в свете ужесточения требований по авиаэкологии. Известия Самарского научного центра Российской академии наук. 2012. Т. 14, №6. С. 307-308.

[60] Rossikhin A.A., Pankov S.V., Khaletskiy Yu. D., Mileshin V.I. Computational study on acoustic features of fan model with leaned stators. Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition: Proceedings of Conference, 16-20 June 2014 y. Düsseldor, Germany, V02AT41A006 (doi: 10.1115/GT2014-26350)

[61] Perullo Ch.A., Tai J.C.M., Mavris D.N. Effects of Advanced Engine Technology on Open Rotor Cycle Selection and Performance. Journal of Engineering for Gas Turbines and Power. 2013. V. 135. P. 071204 (doi:

10.1115/1.4024019)

[62] Hendricks E.S., Tong M.T. Performance and Weight Estimates for an Advanced Open Rotor Engine. 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit: Proceedings of Conference, 30 July - 01 August 2012 y. Atlanta, Georgia (doi.org/10.2514/6.2012-3911)

[63] Zante D.E., Envia E. Prediction of the aero-acoustic performance of open rotors. Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition: Proceedings of Conference, 16-20 June 2014 y. Düsseldor, Germany, V02AT41A008 (doi: 10.1115/GT2014-26413).

[64] General Electric GE90. AERONAUTICA. ONLINE: https://aeronautica.online/engines/general-electric-ge90/

[65] Kwak D., Nomura T., Tokugawa N., Kurita M., Murayama M. Introduction of research project for environmental conscious aircraft technology in JAXA. Greener Aviation Conference: Proceedings of Conference, 11-13 October 2016y. Brussels, 2016. ID 180.

[66] Ben Khelil S., Bardoux Ph., Godard J.-L., Le Garrec T. ZDES Simulation of the noise emission of a regional aircraft main landing gear bay with opened or closed doors. Greener Aviation Conference: Proceedings of Conference, 11-13 October 2016y. Brussels. ID 40.

[67] Geared Turbofan Test Rig. CORDIS: https://cordis.europa.eu/project/id/620152/reporting

[68] High load gear and bearings. CORDIS: https://cordis.europa.eu/project/id/755602

[69] Design of Experiments to Optimize design solutions for a Power reduction Gearbox. CORDIS: https://cordis.europa.eu/project/id/641542

[70] Whurr J. Future Civil Aeroengine Architectures & Technologies. Rolls-Royce: http://www.etc10.eu/mat/Whurr.pdf

[71] Зубчатые передачи и редукторы. ЦИАМ: http://www.ciam.ru/research/strength-reliability/gears-and-gearboxes/

[72] Pure Power PW1000G. PW: https://www.pw.utc.com/Content/PurePowerPW1000G_Engine/pdf/B-1-1_purepower_brochure_ru.pdf

[73] Efficient Shape Optimization of Intake and Exhaust of a Tiltrotor Nacelle. CORDIS: https://cordis.europa.eu/project/id/267309

[74] Innovative counter rotating fan system for high bypass ratio aircraft engine. CORDIS: URL: https://cordis.europa.eu/project/id/605379

[75] Knobloch K., Fischer A., Bake F., Enghardt L., Busse-Gerstengarbe S. Full-scale tests on APU noise reduction. Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition: Proceedings of Conference, 16-20 June 2014 y. Düsseldor, Germany. V02AT41A011 (doi: 10.1115/GT2014-26803).

[76] Солонин В.И., Халецкий Ю.Д. Пути достижения перспективных требований к шуму самолетов гражданской авиации. Экологические проблемы авиации. 2010 с. 11-38

[77] Медведев, В.В., Тимко, О.С. Сравнительный анализ методов снижения шума выхлопной струи авиадвигателя. Научный вестник МГТУ ГА. 2012. №179. с. 57-62

[78] Filippone A., Harwood A. Models, Measurements and Tools for Aircraft Noise. Greener Aviation Conference: Proceedings of Conference, 11-13 October 2016y. Brussels. ID 5.

[79] Grigat E., Hald J. Flight Test Validation of Noise Models for a High Performance Military Aircraft Using Beamforming. Greener Greener Aviation Conference: Proceedings of Conference, 11-13 October 2016y. Brussels. ID 47.

[80] Turboprop and Propfan-Equipped Aircraft Noise Emission Model. CORDIS: https://cordis.europa.eu/project/id/277580

[81] Improvement of Fan Broadband Noise Prediction: Experimental investigation and computational modeling. CORDIS: https://cordis.europa.eu/project/id/12222/reporting

[82] Validation of improved turbomachinery noise prediction models and development of novel design methods for fan stages with reduced broadband noise. CORDIS: https://cordis.europa.eu/project/id/690714/reporting

[83] Simulations of CrOr and fan broadband NoisE with reduced order modelling. CORDIS: https://cordis.europa.eu/project/id/755543

[84] Ferrante P. Francescantonio P., Hoffer P.-A., Vilmin S., Hirsch Ch. Integrated "CFD-Acoustic" computational approach to the simulation of aircraft fan noise. Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition: Proceedings of Conference, 16-20 June 2014 y. Düsseldor, Germany. V02AT41A009 (doi: 10.1115/GT2014-26429).

[85] Filippone A. Development of a New Aircraft Noise Prediction Program. 16th AIAA Aviation Technology, Integration, and Operations Conference: *Proceedings of Conference*, 13-17 June 2016 y. Washington (doi.org/10.2514/6.2016-3902).

[86] Gea-Aguilera F., Gill J., Zhang X., Nodé-Langlois Th. Fan Wake Modeling for Computational Aeroacoustic Simulations of Turbulence-Cascade Interaction Noise. Greener Aviation Conference: Proceedings of Conference, 11-13 October 2016y. Brussels. ID 113.

[87] Redonnet S. Aircraft Noise Prediction via Aeroacoustic Hybrid Methods – Development and Application of Onera Tools over the Last Decade: Some Examples. AerospaceLab Journal. 2014. Issue 7. P. AL07-07 (doi : 10.12762/2014.AL07-07).

[88] Rossikhin A., Pankov S., Brailko I., Mileshin V. Numerical investigation of high bypass ratio fan tone noise. Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition: Proceedings of Conference, 16-20 June 2014 y. Düsseldorf, Germany. V02AT41A007 (doi: 10.1115/GT2014-26354).

[89] Тимушев С.Ф., Гаврилюк В. Н., Аксенов А.А., Клименко Д. В. Моделирование источника и акустического поля тонального шума лопаточных машин. Noise Theory and Practice. 2017. V. 3, №3. P. 19-30.

[90] Havrilesko B.R., Hassan M., Denney R.K., Tai J.C. En Route Jet Aircraft Noise Analysis. AIAA/3AF Aircraft Noise and Emissions Reduction Symposium: Proceedings of Symposium, 16-20 June 2017 y. Atlanta, Georgia (doi.org/10.2514/6.2014-3163).

[91] James M.M., Salton A.R., Downing J.M. Acoustic Emissions from F-35 Aircraft during Ground Run-Up. 21st AIAA/CEAS Aeroacoustics Conference: Proceedings of Conference, 22-26 June 2015 y. Dallas.

[92] Tam Ch. K.W., Parrish S.A. Noise of High-Performance Aircrafts at Afterburner. 20th AIAA/CEAS Aeroacoustics Conference: Proceedings of Conference, 16-20 June 2014 Atlanta, GA (doi.org/10.2514/6.2014-2754)

[93] Fernandez J.A. Contextual Role of TRLs and MRLs in Technology Management. USA: Sandia National Laboratories, 2010. 34 p.

[94] Хаматханова А. М. Готовность к промышленному внедрению как индикатор выбора приоритетных технологических направлений. Экономика науки. 2016. Т.2, № 1. С. 23-34

[95] Technology Readiness Assessment (TRA). Technology Maturation Plan (TMP). Process Implementation Guide. Energy: https://www.energy.gov/sites/prod/files/2014/03/f12/ATTACHMENT-TRA%20Guide%20%20%209-3-13.pdf

[96] General Electric GEnx. Aeronautica: https://aeronautica.online/engines/general-electric-genx/

[97] ПД-14 – главный проект российского двигателестроения. Эксперт online: http://expert.ru/ural/2018/24/pd-14---glavnyij-proekt-rossijskogo-dvigatelestroeniya/

[98] Innovation through evolution. Rolls Royce: https://www.rolls-royce.com/innovation/advance-and-ultrafan.aspx#background

[99] Pratt Whitney ends next generation geared turbofan technology testing. Aeronautica: https://aeronautica.online/2017/10/13/pratt-whitney-ends-next-generation-geared-turbofan-technology-testing/

[100] Авиационные двигатели. ЦИАМ: http://www.ciam.ru/research/engines/aviation/?PAGEN_1=2

[101] European Aviation Environmental Report 2019. European Union : https://ec.europa.eu/transport/sites/transport/files/2019-aviation-environmental-report.pdf

[102] Report by the second CAEP noise technology independent expert panel. Novel aircraft-noise technology review and medium- and long-term noise reduction goals. ICAO:

https://www.icao.int/publications/Documents/10017_cons_en.pdf