TOWARD ACARE 2020: INNOVATIVE ENGINE ARCHITECTURES TO ACHIEVE THE ENVIRONMENTAL GOALS?

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Abstract

The Advisory Council for Aeronautical Research in Europe (ACARE) identified the research needs for the aeronautics industry for 2020:

- Reducing fuel consumption and CO_2 emissions by 50% with 20% for the engine alone
- Reducing perceived external noise by 50%, with 6dB per operation for the engine alone
- Reducing NOx by 80%, with 60 to 80% for the engine alone

Furthermore, since these objectives have been defined the commercial and political pressure to reduce Fuel Consumption and then CO_2 has increased considerably.

In this frame, Snecma is currently developing in parallel three engine architectures answering ACARE 2020 objectives and recent global warning concerns in different ways.

The first architecture is a “balanced” concept between fuel burn, environment and maintenance cost, that relies on the CFM56 experience and on the introduction of very innovative technologies. At 2015-2017 Entry Into Service (EIS), the LEAP56 baseline already reaches a most of ACARE 2020 requirements.

Then, two more radically innovative engine architectures have been identified to go a step further towards two different environmental priorities:

- first one, the Counter-rotating TurboFan (CRTF) is a promising answer, offering a foreseen 20dB cumulative noise reduction, while improving fuel burn in the same amount as advanced conventional turbofans. This concept goes beyond ACARE 2020 goals on noise at a given By-Pass Ratio (BPR), which might become essential especially if optimal BPR slides to non-installable under the wing diameters or noise requirements increase under public pressure.
- second one, the Open rotor architecture is an even more complex concept that delivers a breakthrough on Fuel Burn and CO_2 emissions thanks to an important propulsive efficiency without any duct drag penalties.

Finally, particularly through current European Union (EU) Project VITAL and EU Project DREAM and JTI Clean Sky, Snecma has already started and will continue the detailed assessment of two main general architectures selected to go toward or beyond ACARE 2020 goals. In parallel, Snecma and General Electric (GE) through the LEAP56 program will carry on to build up technological bricks applicable on any of these three architectures in order to be ready to answer any future environmental requirements.

1. Design Strategy regarding environment

1.1 Environmental Goals

The Advisory Council for Aeronautical Research in Europe (ACARE) identified the research needs for the aeronautics industry for 2020, as described in the Strategic Research Agenda (SRA), published in October 2002. Concerning the environment, ACARE fixed, amongst others, the following objectives for 2020 for the overall air transport system, including the engine, the aircraft and operations:

- Reducing fuel consumption and CO2 emissions by 50% with 20% for the engine alone
- Reducing perceived external noise by 50%, with 6dB per operation for the engine alone
- Reducing NOx by 80%, with 60 to 80% for the engine alone

Furthermore, since these objectives have been defined the commercial and political pressure to reduce Fuel Consumption and then CO2 has increased considerably.

Indeed, Fuel Burn share increases in usual market driven operating-cost calculations when fuel price rises and very few experts consider that the fuel price won't follow its inflating path. Therefore, even on short-range aircraft where high maintenance costs usually counteract slight benefit in Fuel burn, trend may change in future in parallel to fuel price.

Subsequently, in a two-year period, the debate over climate change has dramatically changed, especially in USA following Europe, with the general acceptance that global warming is caused by the amount of carbon emitted into the atmosphere, of which the aviation industry contributes about 2-3%. As a result, at the commonly agreed traffic growth rate of 3-5% a year and in spite of technological improvements, the aviation industry faces a moral and economical (taxes, fuel…) challenge that should become the future main requirement. Besides, political debates speed up, illustrated by the European Union (EU) that is presently debating on the introduction of the aviation within the EU Emissions Trading Scheme (ETS).

1.2 Engine design past trends

Since commercial aviation beginning, engines design has been the result of a fine compromise between weight, drag and SFC resulting in Fuel Burn, and speed, costs, noise, emissions and reliability while safety has always been mandatory. Improving thermal and propulsive efficiencies are the two paths to decrease SFC but have collateral negative effects on other parameters.

During the last thirty years, the common trend in turbofan design has been to improve these two parameters by raising components efficiency and temperatures for the first one and above all by increasing the By-Pass Ratio (BPR) for the last one. This trend has been amplified in the past decade by the more and more challenging requirements in terms of noise emissions.

Indeed, fan noise and jet noise are the two largest contributors to engine noise. The trend to increase BPR has had a strong impact on jet noise reduction through decreased jet velocity and has also benefited noise emissions through reduced fan tip speed. Consequently, engine manufacturers have started to propose turbofans with BPR going up to values around 10.

Fig. 1 illustrates the evolution of the Fuel Consumption during the past 40 years.

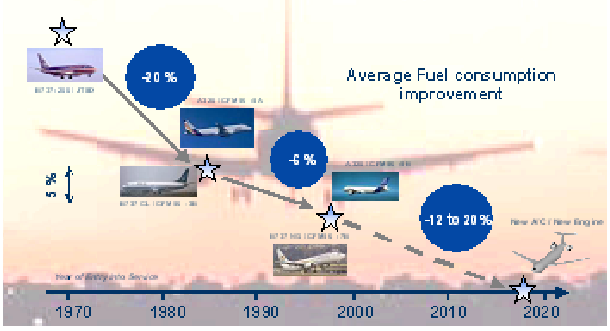

Fig. 1. Fuel Consumption Trend over years

1.3 Design Strategy for the future

With current technologies, the increase in BPR has reached its limit in terms of fuel burn on mission. Although a higher BPR offers a clear reduction in Specific Fuel Consumption (SFC), it also leads to a significant increase of engine weight as well as nacelle and installation drags. Above an optimum BPR value, the penalties brought about by weight and drag, offset the benefits provided by higher BPR.

The challenge that is proposed today to engine manufacturers is to find technology solutions that will enable the use of higher BPR architectures without inducing fuel burn penalties whilst providing an optimum BPR value.

In this frame, Snecma, together with GE, is currently developing in parallel three engine architectures answering ACARE 2020 objectives and recent global warning concerns in different ways.

The LEAP56 program is a “balanced” concept between fuel burn, environment and maintenance cost, that relies on the CFM56 experience with similar architecture but also on the introduction of very innovative technologies such as new metallic and composite materials, improved 3D aerodynamic…

Then, two more radically innovative engine architectures have been identified to go a step further towards two different environmental priorities:

- A new fan concept, Low speed Counter-rotating Turbofan (CRTF) that reduce noise levels and fuel burn without the need to significantly increase the nacelle diameter.

- Open rotors architectures, which are well known as the best concepts for SFC and Fuel burn but with more limited noise improvements.

2. Balanced concept: Baseline

2.1 Concept Target and main properties

Timed for a target service entry of 2015-2017, this architecture is aimed at producing an engine with 13-17% lower specific fuel consumption than current available engines, 15% lower maintenance costs, up to 15dB lower cumulative noise levels and 25% longer life-on-wing.

This baseline is the best compromise for a fuel price around 100$/barrel because of its relative simplicity with a low part counts (therefore reduced maintenance cost), and high reliability. At current EIS target, this baseline already reaches a most of ACARE 2020 requirements.

The engine would produce lower nitrous oxide and other emissions than the CAEP/6 standards due for introduction from 2008. It will also have a higher bypass ratio of 10:1 versus 5:1 on CFM56 engines, and a High Pressure (HP) pressure ratio of more than 17:1 against the 11:1 of today's high-pressure spools. Although, a two-stage HP turbine concept has been studied to achieve this result, the best performance is reached with a 15% higher loaded single HP turbine stage and an eight-stage HP compressor.

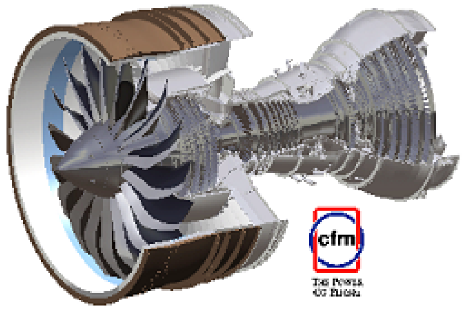

Fig. 2. Baseline Engine

2.2 Advanced technologies

Even though, the global architecture is similar to CFM56 engines, this baseline is a highly innovative Turbofan that includes, in addition to a great reduction of number of stages and airfoils, a remarkable amount of advanced technologies: amongst others, a resin transfer-molded 3D woven composite fan blade set, that greatly reduces weight and allows increased BPR, a composite fan case, next-generation 3D aerodynamically designed HP compressor and turbine, advanced low-pressure turbine with titanium aluminide blades…

Fig. 3 hereunder shows the time scale of different advanced technologies developed by Snecma for the next CFM56 engine.

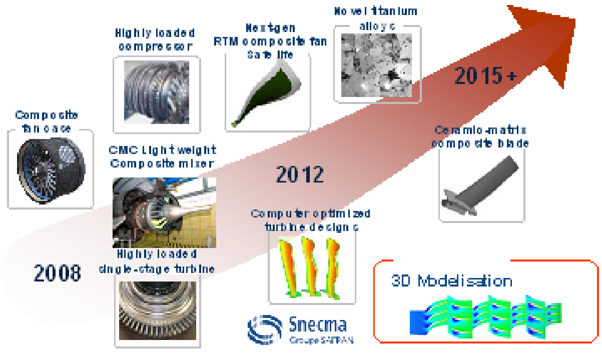

Fig. 3. Weight reduction & Aerodynamic improvement

3. Noise oriented concept: CRTF

3.1 Concept Target

The EIS targeted for this architecture is 2015-2017. The main objectives are a 17% lower Fuel Burn, 20% longer life-on-wing and a 20-22EPNdB reduction in cumulative noise which go beyond ACARE 2020 target. At same BPR and technological level, this architecture should bring about a 5dB benefit and is consequently identified as a cut noise concept, which might become essential especially if optimal BPR slides to non-installable under the wing diameters or noise requirements increase under public pressure.

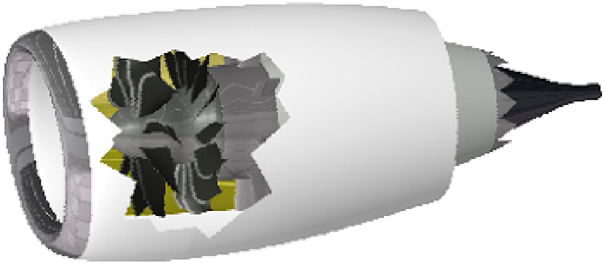

Fig. 4. CRTF Engine

3.2 Concept principles

The aim of this concept is to reduce the fan tip speed without a reduction gearbox that induces losses in efficiency and reliability. This solution consists of two contra-rotating fan stages, mounted on contra-rotating shafts linked to a low-pressure turbine with contra-rotating blade rows.

Fig. 5 describes the macro-design of the CRTF with the HP Core rotor in green, the Low Pressure (LP) front fan and turbine rotor in blue and the LP rear fan and turbine rotor in red.

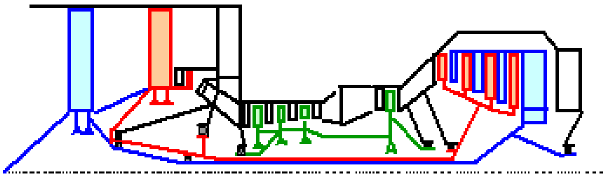

Fig. 5. CRTF Architecture scheme

Replacing the conventional fan by a dual stage counter-rotating fan is a good solution to reduce the diameter constraint: indeed, overall secondary pressure ratio can be kept at a rather high value (~ 1,4 to 1,6), which enables having a reduced fan diameter. This overall secondary pressure ratio is then split between two low pressure rotors whose performance can be achieved at reduced rotational speed, hence achieving noise reduction target.

The fan module being directly linked to the kinetic energy of the rotating parts, this concept provides, at same technology level, a weight reduction. It is estimated that thrust to weight ratio of the corresponding whole engine is increased by 10 to 12%.

Two main options can be used for CRTF engine design versus equivalent turbofan:

Design 1 : Maximum noise improvement

This option uses the whole potential of LP rotational speed reduction to drastically reduce fan noise. Even though fan rotational speed is highly reduced, fan pressure ratio for the CRTF (both rotors accounted for) remains equivalent to the conventional turbofan engine. Engine bypass ratio and SFC remain then similar to the turbofan. Engine diameter is slightly reduced since CRTF shows a slightly better specific airflow capacity than turbofan. Engine weight is equivalent to turbofan, since increased LP turbine weight is balanced by lighter low speed fan rotors. Resulting fuel burn for this CRTF design option is similar to turbofan.

Design 2 : Medium noise improvement and fuel burn improvement

This option doesn't take advantage of the whole fan rotational speed decrease potential, in order to have a slightly increased fan pressure ratio. This higher fan pressure ratio leads to a reduced BPR, and noticeably reduced fan diameter. Engine weight is then reduced as well as engine drag, leading to an improved fuel burn level.

These 2 options are summed up on the following diagram, showing the overall fans pressure ratio trend for both conventional turbofan and CRTF, as a function of LP rotational speed:

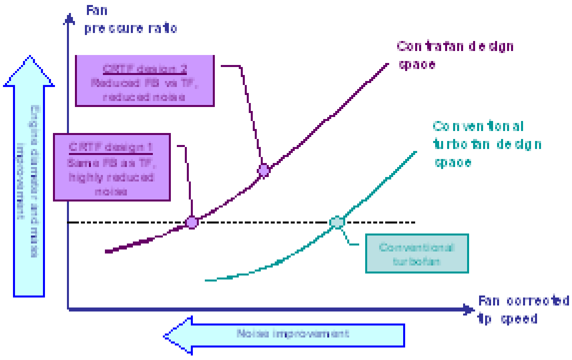

Fig. 6. CRTF design options

The second design option is currently the one preferred, balancing noise improvement (around 4 Effective Perceived Noise level in deciBels (EPNdB) versus conventional turbofan at same technology level) and fuel burn benefit (around 1 % versus turbofan at same technology level).

3.3 VITAL Studies

The Contra-Rotating TurboFan (CRTF) is particularly developed and tested by Snecma within the European Union FP6 VITAL Project.

The main components investigated in VITAL in order to prove the feasibility and level of general performance of the concept are:

- Low speed contra rotating fan that tackles low Fuel Burn through efficiency and lightweight components, and low noise through low fan tip speed

- New low speed low-pressure compressor (booster) concepts and technologies for weight and size reduction

- New lightweight structures using new materials as well as innovative structural design and manufacturing techniques

- New Metallic Matrix Ccomposite (MMC) shaft technologies enabling the high torque needed by the new fan concepts through the development of prototypes that will be tested

- New contra rotating slow low-pressure turbine (LPT) technologies for weight and noise reduction

- Optimal installation of Very High BPR (VHBR) engines related to nozzle, nacelle, thrust reverser and positioning to optimise weight, noise and fuel burn reductions.

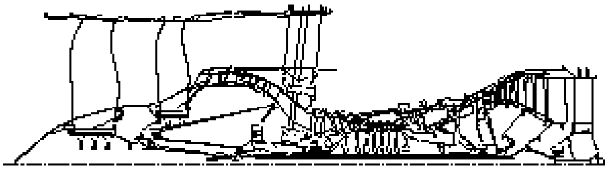

Fig. 7. CRTF X-section

This radically innovative concept will reduce noise levels and fuel burn without the need to significantly increase the BPR and new lightweight technologies are studied to compensate the weight penalties induced by the added components.

These technologies will be tested and validated during aero-acoustic Wind-Tunnel Test (WTT) and mechanical rig tests in order to bring the Technology Readiness Level (TRL) of these technologies to a level ranging between 3 (proof-of-concept) and 5 (Module and/or subsystem validation in relevant environment).

3.4 VITAL Achievements

In 2005, Snecma made a first design called CRTF1 with the support of CIAM and DLR for aerodynamic, acoustic and mechanical evaluation.

In 2006, CIAM and Comoti have manufactured the mock up hardware of the CRTF1 module and adaptation parts for the test bench. All of them are available for tests. In parallel, a large concept study project was launch in between DLR, CIAM, Cenaero, with ONERA and UPMC support, in order to study CRTF1 design and potential improvement using the state of the art of the advance aerodynamic and acoustic design tools.

In 2007, three tasks have been managed in parallel with CRTF1 mock up tests started in C3-A anechoic chamber at CIAM, Russia, SRF final detail studies and manufacturing performed by COMOTI, Romania, and design of 2 optimized Contra Fan that exploit the conclusions of the advance studies performed in 2006.

4. Fuel Burn / CO_2 oriented concept: Open Rotors

4.1 Targets

The major aim of this architecture is to answer the recent and growing pressure on aviation industry to tackle faster and deeper the global warming issue. Therefore, the main target is to reduce fuel consumption and CO_2 emissions up to 7% beyond the ACARE 2020 objectives, which means 22-28% lower Fuel burn versus 2000 engines. This step will primarily be achieved thanks to the very high propulsive efficiency reached compared to an equivalent Turbofan with a BPR around 40 and to the weight and drag benefit of duct non-existence.

However, this breakthrough is achieved at the expense of moderated noise reduction with a targeted reduction of about 9EPNdB in cumulative noise, considering the fact that at same state of the art an Open rotor is intrinsically noisier than an equivalent (same thrust) high bypass ratio turbofan engines. To reach better noise level, an aircraft dedicated installation becomes necessary to take benefit from shielding effects.

At the same time, the level of reliability have to be at the same level as current engines; which is not the easiest target as this architecture is noticeably more complex than current ones.

The EIS targeted for this architecture is 2018+.

Fig. 8 presents the Fuel burn versus cumulative noise design space for open rotors.

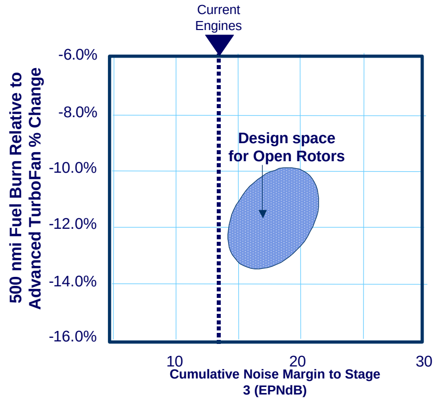

Fig. 8.Open Rotors FB vs Noise design space

4.2 Concept principles

The engine global efficiency can be defined using the following quantities :

- Thermal efficiency (η_{th}) is defined as the ratio of the output power given by the engine to the airflow, to the input energy amount given by the fuel combustion.

- Propulsive efficiency (η_{pr}) is defined as the ratio of the power given to the aircraft (thrust work) to the power given by the engine to the airflow.

- Thermopropulsive efficiency (η_{thp}) is defined as the ratio of the power given to the aircraft (thrust work), to the input energy amount given by the fuel combustion:

$$\eta_{thp} = \eta_{th} \times \eta_{pr}$$

Thermal efficiency is addressed through component efficiency and temperature.
Propulsive efficiency is mainly addressed through BPR. Indeed, the following figure illustrates the links between first Fan Pressure Ratio (FPR) and BPR and then between BPR and propulsive efficiency.

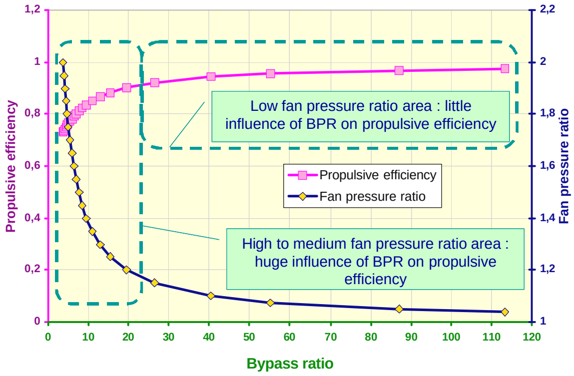

Fig. 9. Propulsive efficiency and FPR function of BPR

Therefore, reaching high propulsive efficiency requires high BPR but BPR higher than 15-20 can’t be reached with a turbofan as theoretical propulsive efficiency would be far outweighed by nacelle drag and weight. Therefore, this kind of BPR is associated, even for far term future, to unducted concepts like turboprop or open rotors.

Subsequently, key gains of open rotors versus turboprops are induced by the improved propulsive efficiency and the limited diameter.

In fact, an important source of losses for single propeller is the rotational energy wasted in the swirl at the propeller exhaust, since only the axial component of the resulting effort on the blade is a real contributor to the thrust, as shown in the following figure.

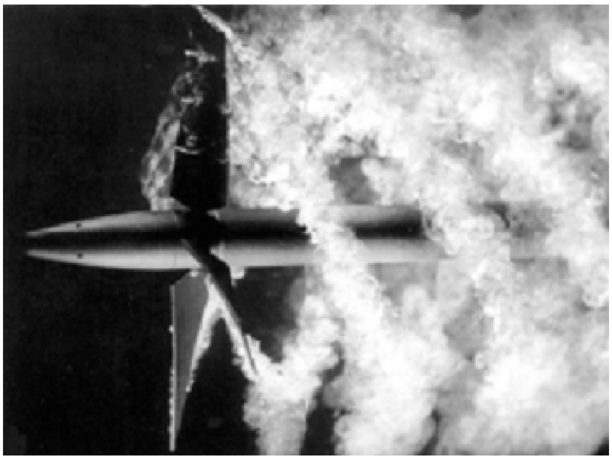

Fig. 10. Single propeller swirl

Besides, for a single propeller, the only solution to deal with high power levels while maintaining an acceptable efficiency is to increase the propeller diameter, which turns out to be a problem for engine integration on aircraft. Sharing the global propeller load between two propellers helps improving the efficiency, while global propeller diameter remains acceptable for aircraft integration.

Fig. 11 hereafter presents a comparison between propulsive efficiency of turbofans, turboprops and open rotors:

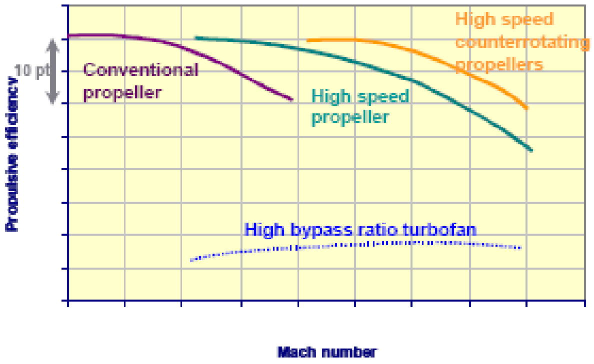

Fig. 11. Relative propulsive efficiency

4.3 Engine design challenges

Open rotor engines design raises major challenges that need to be addressed and resolved (in no particular order):

- Improve propeller efficiency to reach ambitious CO_2 reduction targeted. To comply with this requirement, new 3D RANS CFD codes were calibrated on 80's results and optimised for this kind of application and finally coupled with optimisation software. Then, WTT at low and high speed will validate predictions.

- Reduce both community and cabin noise even if Open rotor engines are intrinsically noisier than ducted concept. To achieve this goal, new 3D RANS CFD unsteady codes were calibrated on 80's results and optimised for this kind of application and finally coupled with optimisation software. Then, WTT at low and high speed will validate predictions.

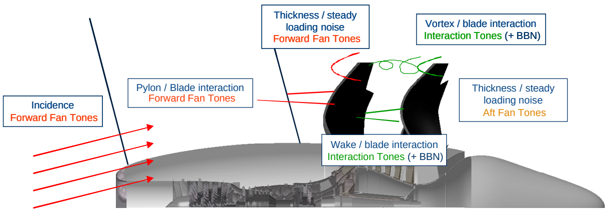

Fig. 12. Propeller Acoustic sources

- Improve Mechanical design of the propellers to ensure that safety of open rotors engines would be equivalent to turbofan, especially regarding fatigue and bird ingestion. This point is a showstopper as safety is never a compromise.

- Answer certification questions over the type of engine certification to be applied, Turboprop or Turbofan. Moreover, engine burst issues are to be tackled at Aircraft level depending on the engine architecture and aircraft installation configuration.

- Make Pitch change mechanism as simple and reliable as possible to obtain an overall engine reliability at least equivalent to current engines. For this purpose, multiple brainstorming and advanced-concepts are performed and assessed. This component will then be rig tested.

- If required by the concept, design a Power Gear Box (PGB) as reliable and efficient as possible. PGB has certain advantages, which needs to be less than compensated by commonly known drawbacks that are reliability, durability, safety, cost increase, efficiency losses and thermal management.

- To prove engine operability at low power with a more electric configuration. Indeed, core size resulting from open rotor concepts design is low compared to equivalent Turbofan while Aircraft power demands remain the same.

4.4 Engine design options

Then, once the general assumptions have been set up, a large number of degree of freedom is still available to reach the best configuration, with for instance concepts with or without a Power Gear Box, the propellers located in front (Puller) or at the rear (Pusher) of the Gas generator… Consequently, each relevant concept has been studied in details to compel the pros and cons in order to build a first rating of the different configuration regarding the different criteria of selection. These studies will carry on and be completed during the course of DREAM and JTI CLEAN SKY to select the best-optimised configuration.

Fig. 13 describes the macro-design of the Counter-Rotating (CR) Direct Drive Pusher design, as an example of open rotor architecture, with the HP Core rotor in green, the Intermediate Pressure (IP) core rotor in yellow, the free turbine front propeller rotor in orange and the free turbine rear propeller rotor in pink.

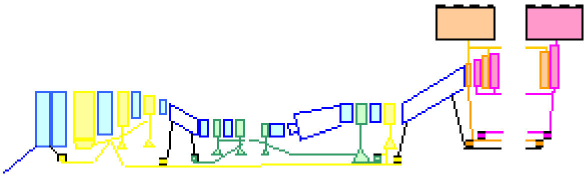

Fig. 13. CR DD Pusher Architecture Scheme

Fig. 14 hereunder shows four concepts designed and assessed by Snecma, amongst others: a CR Direct Drive Pusher, a CR Pusher with a PGB, a CR Puller with a PGB and a Single propeller Puller with a PGB.

Fig. 14. Snecma Open rotor Concepts

The CR Direct Drive Pusher concept is the reference, as characteristics of this concept are well known thanks to 80’s GE engine studies called GE36 in which Snecma owned a 35% share. The noise margin used for Pushers includes pylon blowing at Take-Off to decrease the interaction between wakes of the pylon and the front propeller.

The CR Pusher with PGB concept is slightly lighter thanks to an important reduction in number of power turbine stages and slightly less noisy thanks to a reduction in propeller rotational speed. These gains are obtained with a PGB but at the expense of worse maintenance costs, as the complex gear assembly is a relatively low reliable component.

The CR Puller with a PGB concept is slightly heavier and noisier with a supplementary deficit on performance because of the inlet efficiency penalty.

4.5 Aircraft integration

In addition to key Open Rotor issues and concepts relative rating, the Aircraft integration is a subject by itself as the installation of an Open rotor engine will need a close and strong work with Airframers to develop an optimise configuration for both performance and acoustic while solving certification issues.

The challenge of installing an Open rotor on a short-range aircraft is primarily linked to the important size of the propellers and to the no-duct configuration.

Snecma has started to study different aircraft configurations and Fig. 15 shows four Aircraft installation configurations, amongst others: a CR Pusher installed on sides of rear fuselage, a CR Puller installed on sides of rear fuselage, a CR Puller under high-wing and a CR Pusher over wing for acoustic shielding.

Fig. 15. Four Aircraft integration concepts

Each configuration has pros and cons that need to be assessed regarding the following main criteria: Community noise and Cabin noise, Aircraft Certification aspects, installed engine performance and overall aircraft performance and Aircraft balance.

Preliminary main conclusions of the Aircraft installation evaluation are the following:

- Configurations with acoustic shielding are promising but includes high risks on certification aspects and minor risks on installation drag
- Configurations under or over wing should bring some benefits regarding certification aspects and family extension but are highly risked for cabin noise since the only solutions are cabin passive treatment (inducing weight) and/or active devices.

4.6 European projects

The Open Rotor concept is currently developed and tested by Snecma within the European Union FP7 DREAM Project. This project should have a full duration of 3 years with a termination at the end of 2010 and brings together 47 partners.

DREAM will deliver integrated technologies at TRL 4-6 by studying and testing these advanced technologies mainly devoted to fuel consumption / CO_2 reduction, pollution reduction, whilst retaining acceptable noise levels. For instance, several intensive aero-acoustic WTT campaign will be performed at low and high speed to verify both efficiency and noise levels of propellers.

These technologies will constitute candidates ready to be used for the CLEAN SKY engine platform, which is the direct global exploitation path for DREAM. In CLEAN SKY, a selection of engine architectures will be made on the basis of the results of VITAL, NEWAC and DREAM to develop engine demonstrators. Snecma will develop a counter-rotating open rotor engine for the Smart Fixed Wing Aircraft demonstrator in CLEAN SKY and in other potential collaborative programs.

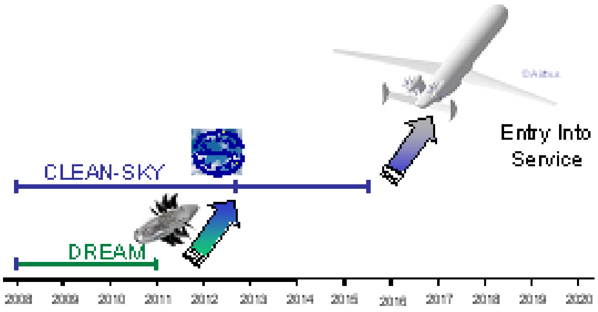

Fig. 16. EU Open rotors projects

5. Conclusions

Following ACARE 2020 objectives that tackle Fuel Burn, noise and emissions, and the recent growing sense of urgency regarding climate change and especially aviation impact, engines designed for future Short-range aircrafts that will replace A320s and B737s will have to fulfil requirements presented in Fig. 17, which correspond to existing criteria with a greatly amplified influence of noise and emissions.

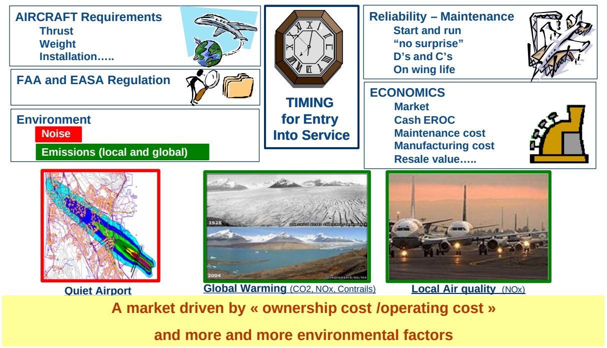

Fig. 17. Engine design criteria

To answer this challenge, Snecma has considered three different architectures that reach different targets as presented in following Fig. 18.

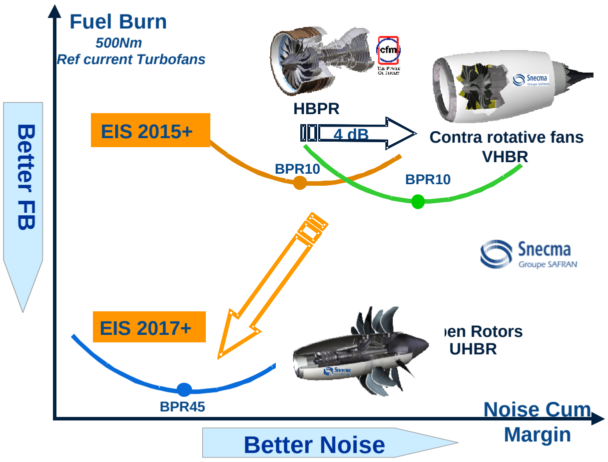

Fig. 18. Architectures Fuel burn versus Noise

The baseline LEAP56 is a balanced engine resulting from a compromise between main criteria that could answer ACARE goals depending on the EIS. At 2015-2017 EIS milestone target, the LEAP56 baseline already reaches most of ACARE 2020 requirements.

Then, the CRTF is a concept that goes beyond ACARE 2020 goals on noise associated with a Fuel burn improvement depending on design option selected.

Finally, the Open rotor architecture is a concept that delivers a breakthrough on Fuel Burn and CO_2 emissions thanks to a great propulsive efficiency and no duct penalties. Nevertheless, some key challenges remain to be answered: Community and cabin noise, certification and reliability.

With this multiple concepts strategy, Snecma, together with GE, has defined a plan to develop several architectures relevant for the Short-range aircrafts replacement coming in the next decade, whatever is the environmental challenge that prevails: noise or emissions.

Indeed, particularly through current EU Project VITAL, DREAM and JTI CLEAN SKY, Snecma has already started and will continue the detailed assessment of two main general architectures selected to go toward or beyond ACARE 2020 goals. In parallel, Snecma and GE through the LEAP56 program will carry on to build up technological bricks applicable on any of these three architectures.

6. References

[1] enVIronmenTALly Friendly Aero Engine
Annex 1 – "Description of Work"

[2] valiDation of Radical Engine Architecture systeMs Annex 1 – "Description of Work"

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